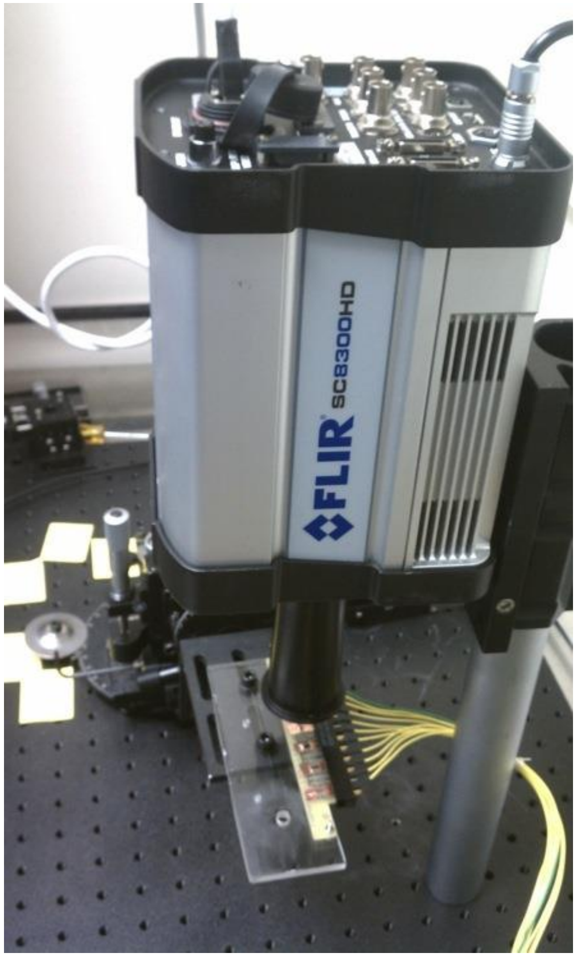
Thermal Signature of a Resistor

And Problems Encountered Along the Way

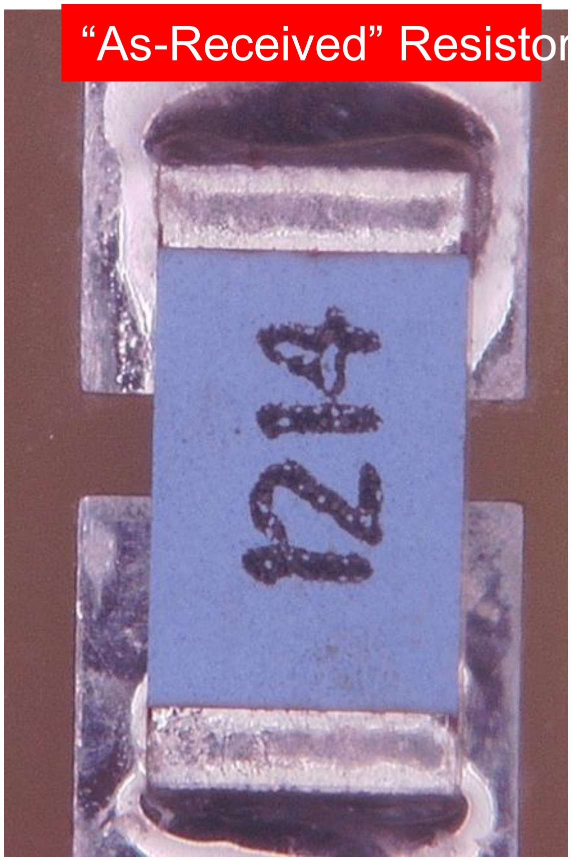
Jack Shue, Jay Brusse, Lyudmyla Panashchenko

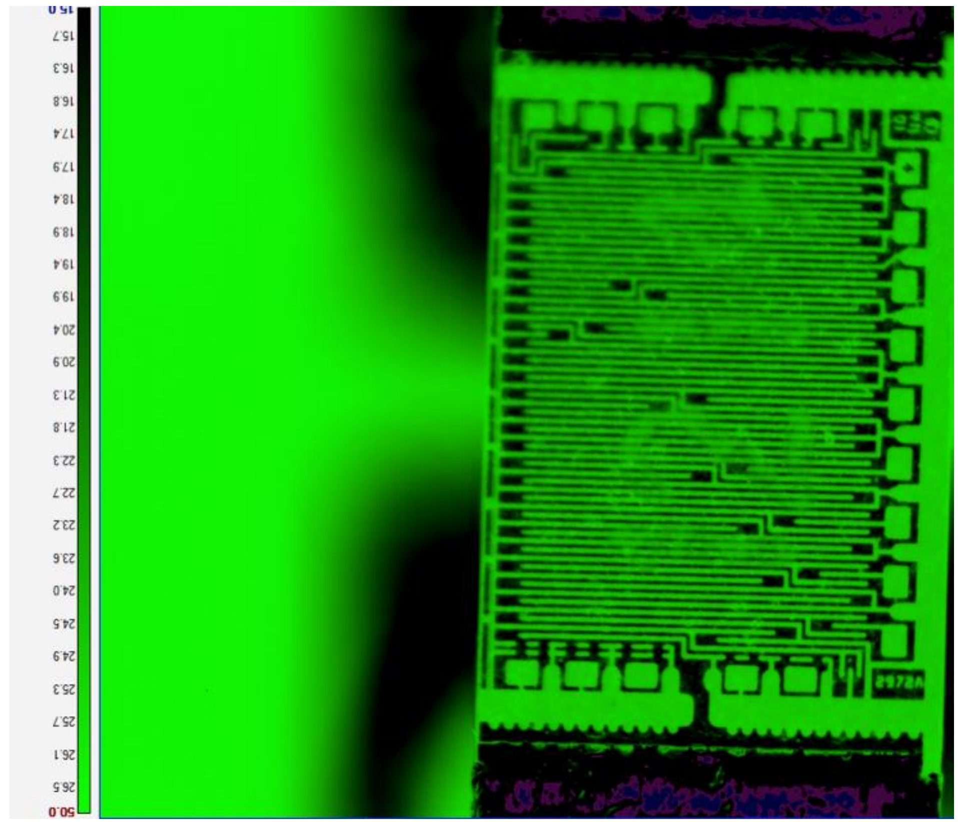
FLIR SC8300HD
High Resolution Infrared Camera
+ 4X Lens

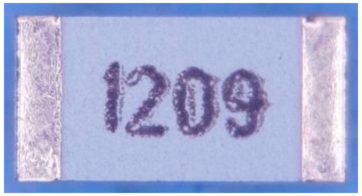


Surprise!!

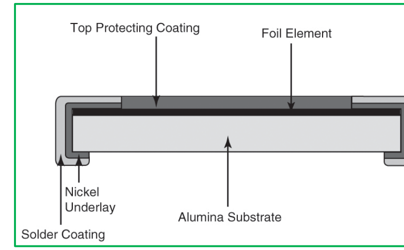
With This Particular Camera/Lens Configuration We Could See THROUGH THESE SPECIFIC External Coatings and Image the Resistor Pattern Even When Device is NOT POWERED







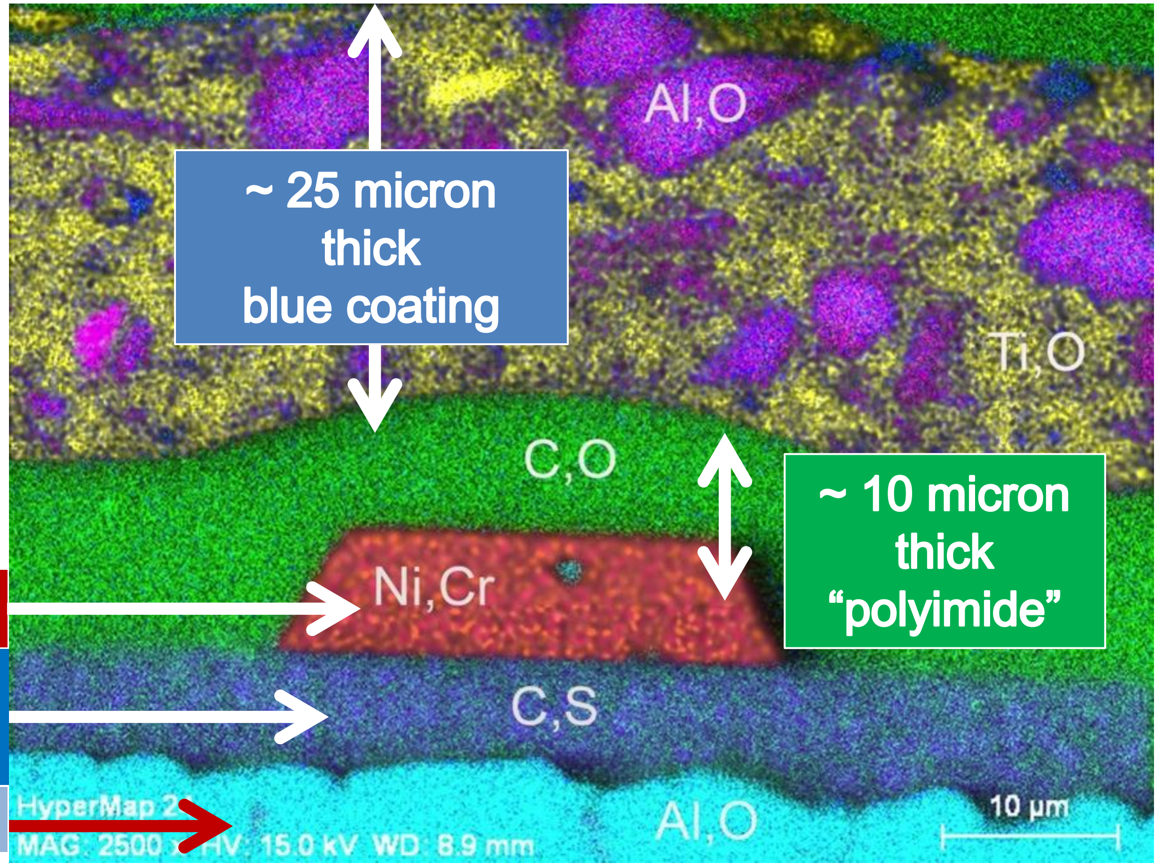
This is what we could "See Through" Cross Section of Resistor



Resistor

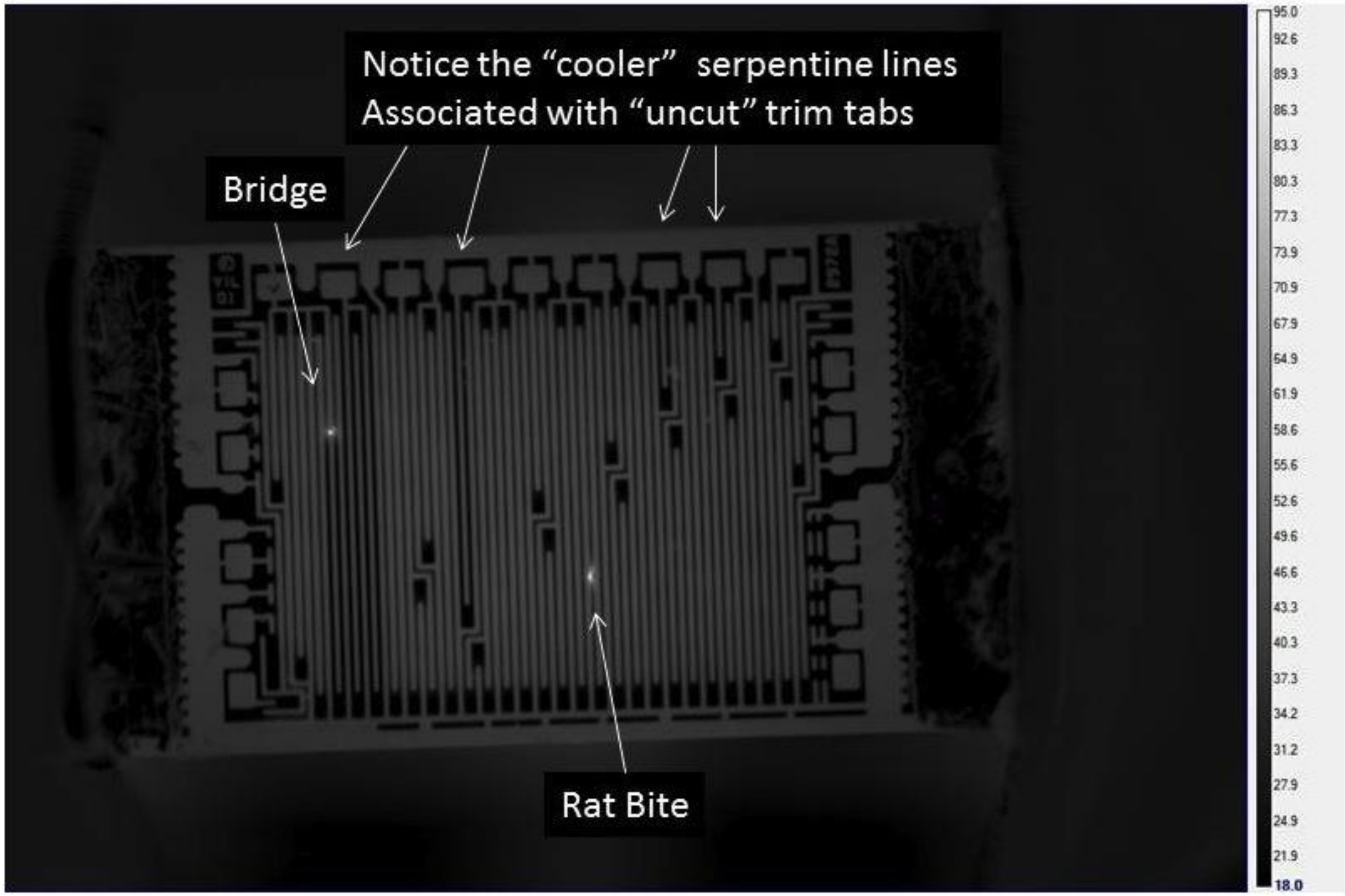
Bonding Adhesive

Alumina Substrate



An EDS map of a cross-sectioned resistive element resting on a carbon-sulphur compound on the alumina substrate of the device. The resistive element is coated with a hydrocarbon layer. The protective cover consists of aluminum and titanium oxide particles embedded in a polymer matrix.

Infrared Image of a 2kOhm Size 1206 Foil Resistor Receiving Power



Why We Worry about a Resistor.

- Spacecraft are expensive to build and are usually one of a kind
- We want our spacecraft to last a long time
- **<u>Sometimes…Parts fail!!!</u>**
- Fixing a spacecraft once in orbit is almost always NOT POSSIBLE!
- Because of the above, ideally, we strive to employ effective screening tests to reduce in-flight failure rates by finding weak parts BEFORE they are used.

Why We Worry about a Resistor.

- Experience tells us that the resistor in question has some known failure modes DESPITE the use of several different screening tests. These screening tests are LEAKY and may allow a few weak parts through!!!

Can we find a better screening process to find weak parts?

Goal of this Paper

While working on a new screening process for precision foil resistors, there were issues between the IR camera and the test article that all came together in textbook fashion. This paper talks about some of those issues.

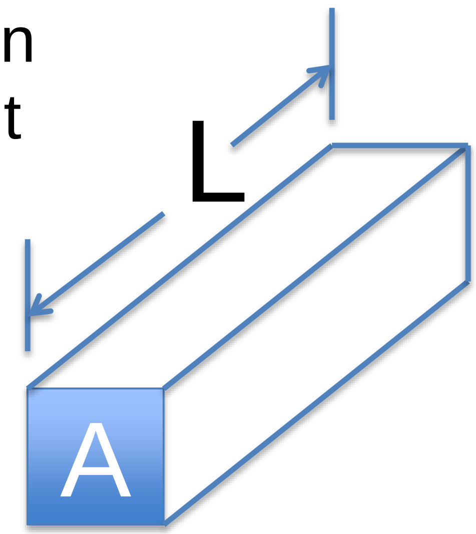
In this paper

- What is a foil resistor?
- Unavoidable problems
- Why Thermal Imaging
- The need for a microscope and the problems it represents
- Problems encountered
  - Size and wavelength limitations
  - Moiré patterns
  - Pixel size limitations
  - Emissivity and reflections

There is nothing new or unusual about these problems but they come together when working on the resistor.

What is Resistance

The electrical resistance of an electrical conductor is the opposition to the passage of an electric current through that conductor.



$$R_{\cancel{\Omega}} = \rho_{\cancel{\Omega m}} \frac{L_{\cancel{m}}}{A_{\cancel{m^2}}}$$

ρ for Copper = 0.000,000,016,78 Ωm =16.78e-9 Ωm

ρ for Silver = 0.000,000,015,87 Ωm = 15.87e-9 Ωm

Where R = resistance (ohms)

ρ = resistivity of the material (ohms · meters)

L = length of the material (meters)

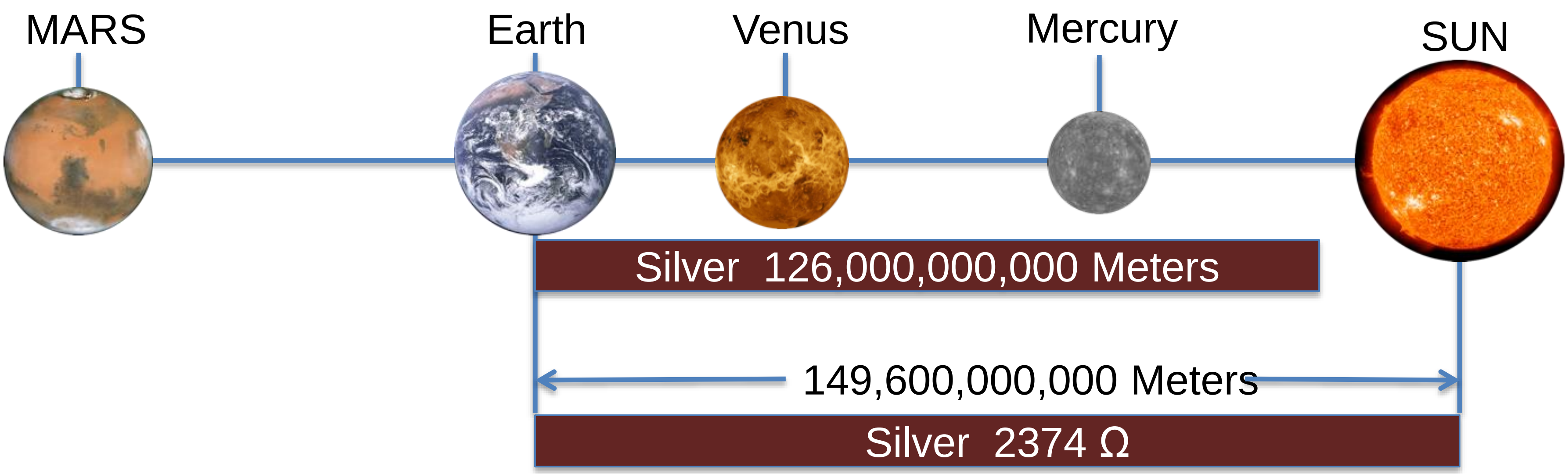
A = cross sectional area of the material (meters^2)

How to Build a 2000 Ω Resistor

Starting with a block of Silver that is 1 meter wide by 1 meter thick (i.e., 1 m^2 Cross Sectional Area), How LONG would the block have to be to make a <u>2000</u>Ω Resistor?

ρ for Copper = 0.000,000,016,78 Ωm =16.78e-9 Ωm
ρ for Silver = 0.000,000,015,87 Ωm = 15.87e-9 Ωm

$$R_{\cancel{\Omega}} = \rho_{\ \cancel{\Omega m}} \cdot \frac{L_{\cancel{m}}}{A_{\ \cancel{m}^{\cancel{2}}}}$$



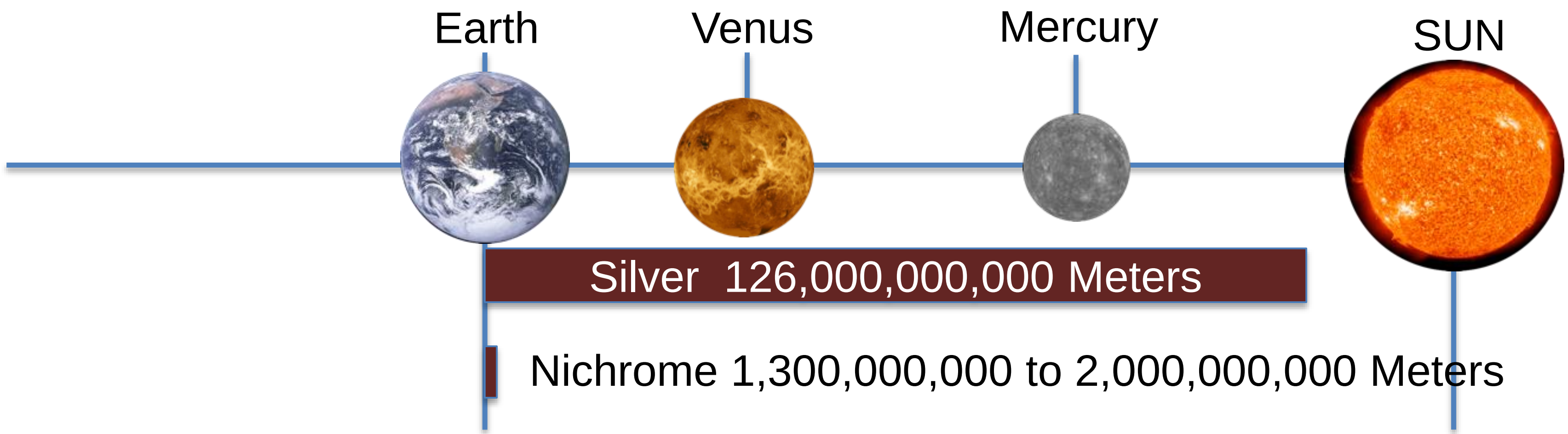
Improvements in the Size – Part I

Choose a Different Material with a different RESISTIVITY!!!

Nichrome (Nickel Chromium Alloy) alloys are commonly used to make resistors.

$$R_{\cancel{\Omega}} = \rho_{\cancel{\Omega m}} \cdot \frac{L_{\cancel{m}}}{A_{\cancel{m}^{\cancel{2}}}}$$

ρ for Nichrome = 1 e-6 to 1.5 e-6



A factor of approximately 100 better!

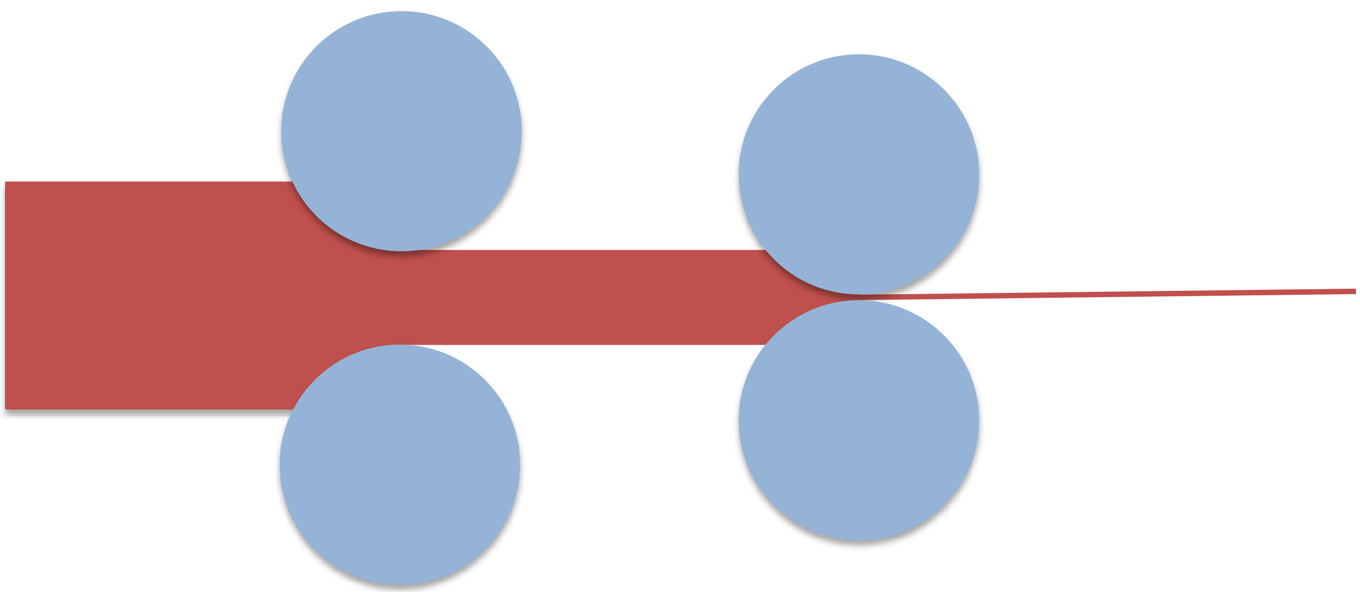
But that is still 4.3 times the distance from the earth to the moon!

Improvements in the Size – Part II

Reduce the Cross Sectional AREA of the Conductor and it will NOT have to be So Long!!!

$$R_{\cancel{\Omega}} = \rho_{\cancel{\Omega m}} \cdot \frac{L_{\cancel{m}}}{A_{\cancel{m}^{\cancel{2}}}}$$

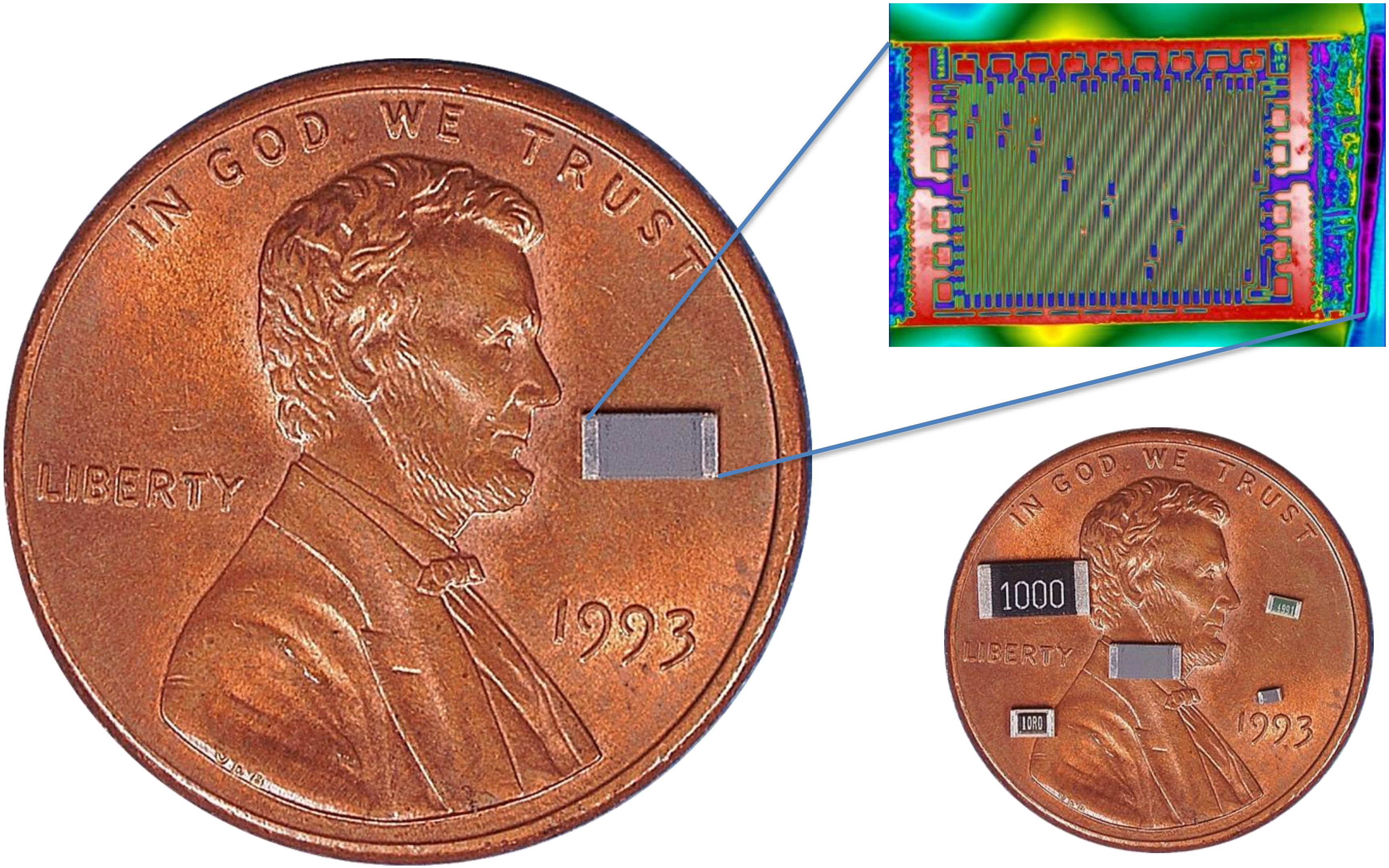
For this Resistor Technology the Nichrome can be reduced in width and thickness from 1 meter^2 down to ~0.000002 meter x 0.000002 meter, which means the length needed for 2000 ohms becomes **~ 1 cm long.**



This is a reduction in area of **12 orders of magnitude**!

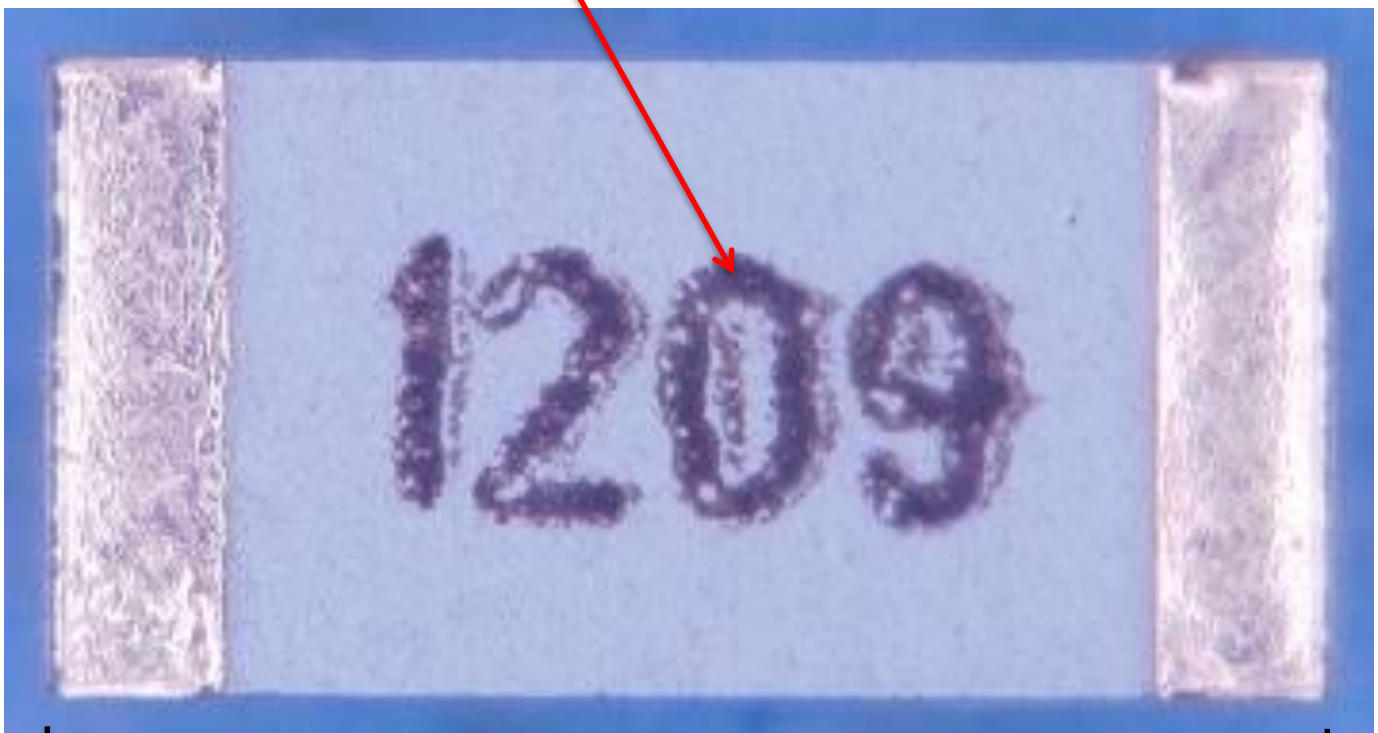
Now THAT'S Much More Practical!

Resistor to Scale



Resistor Part of Interest

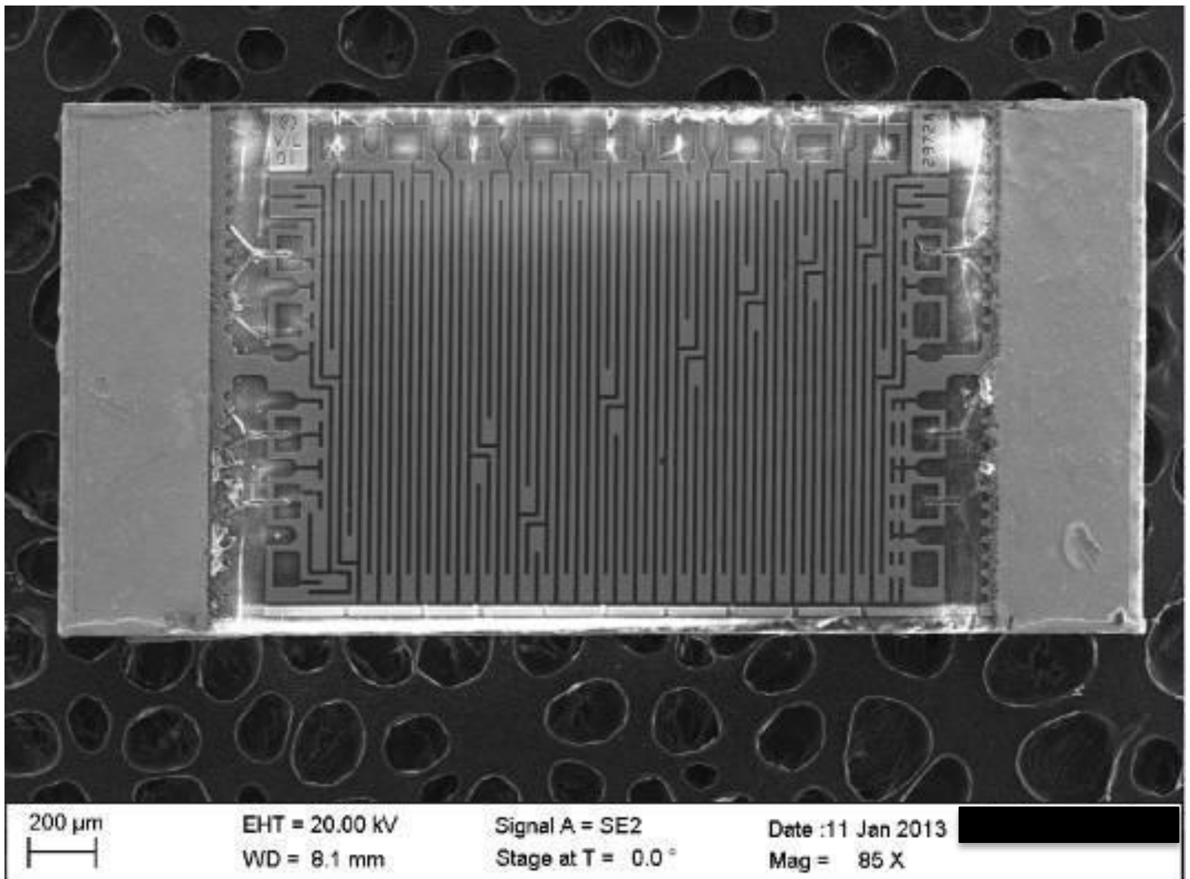
Date Code: 9th week of 2012



0.060 Inches
0.0015 meters

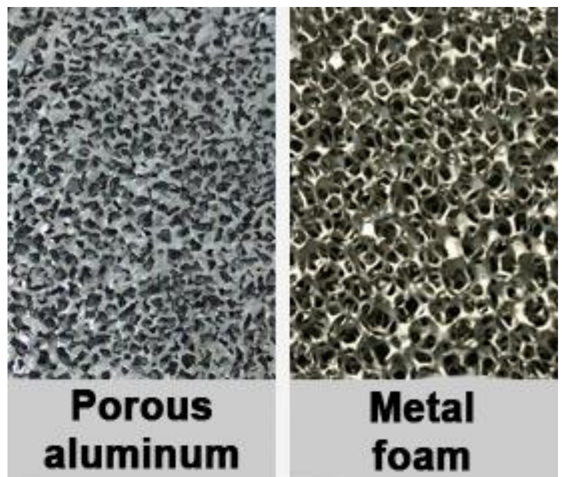
0.120 inches
.00305 meters

Scanning Electron Microscope (SEM) Image of Resistor Without Blue Coat

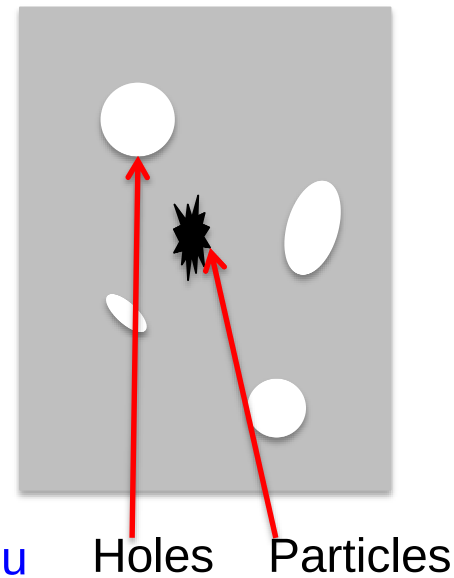


What Happens to Thin Metals

Household Aluminum Foil
0.000,016 meters thick



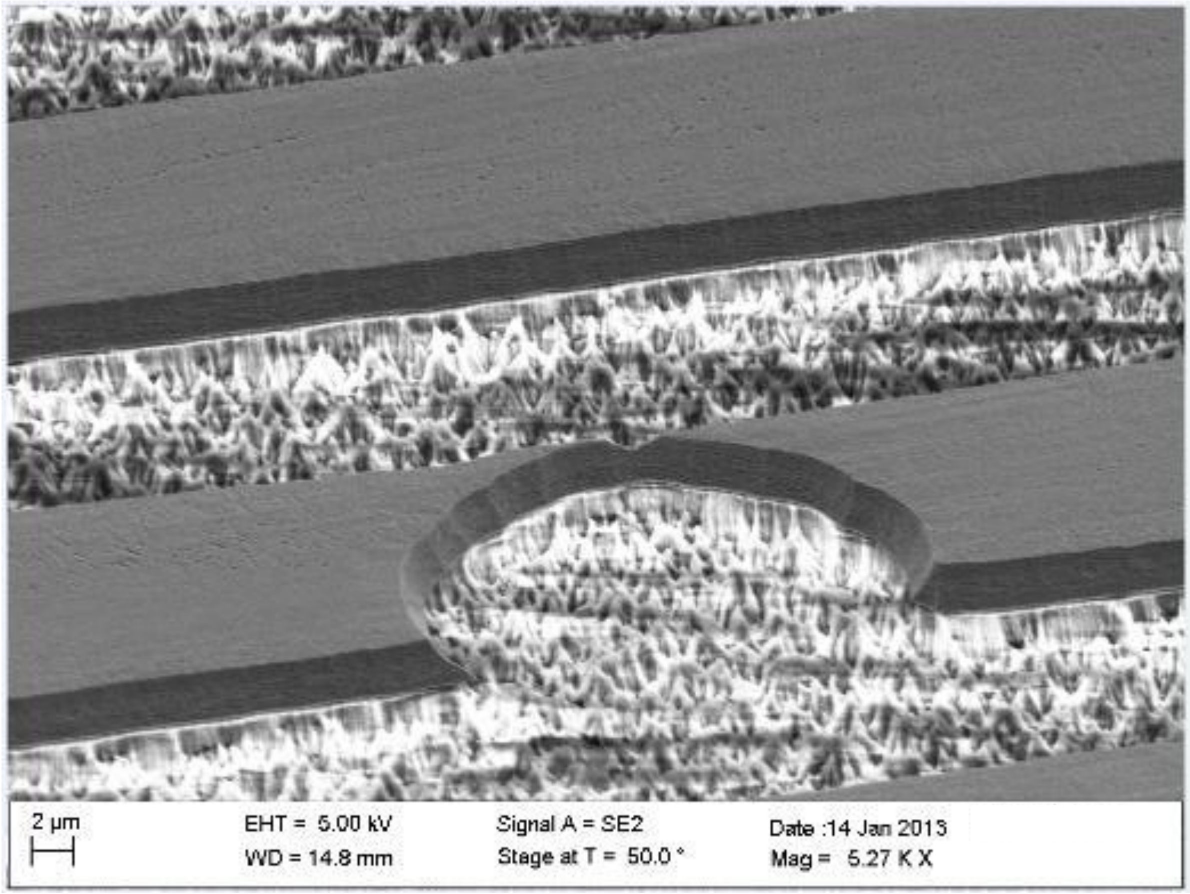
A foil 0.000,001 meters thick



http://b2bimg.bridgat.com/files/Porous_aluminum_An_Alternative_to_Sintered_Metals.jpg

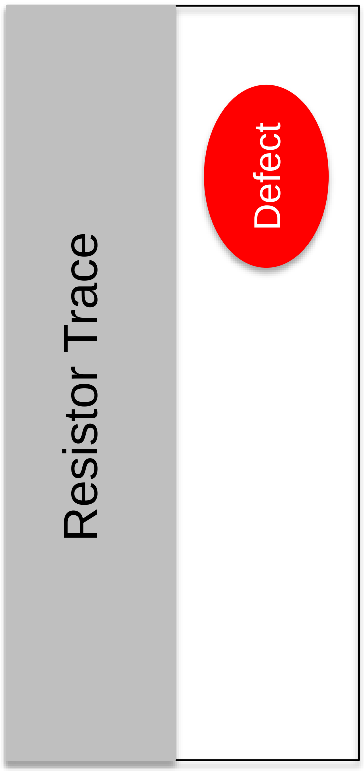
Metallurgists describe this as a metal becoming **porous**

Nichrome Foil Resistor with a “RAT BITE”
(May Be Caused by Working with a “Porous” Foil)

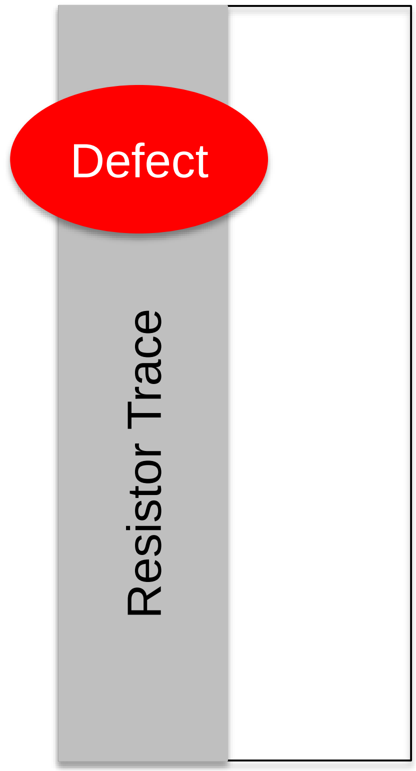


What do “Defects” do to Resistance?

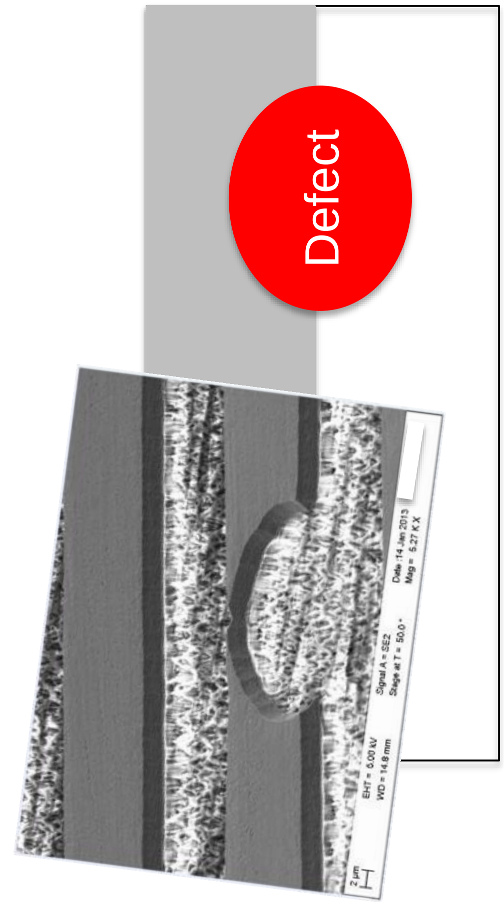
No Effect



Open Circuit
No Resistor

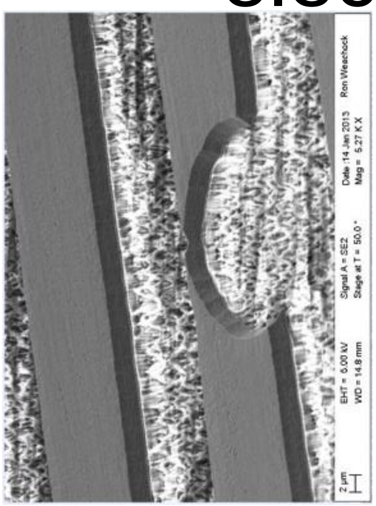


? See next slide



Change in Resistance

A rat bite at one location where 90% of a trace is missing before it can be electrically **detected** (Maybe*) .

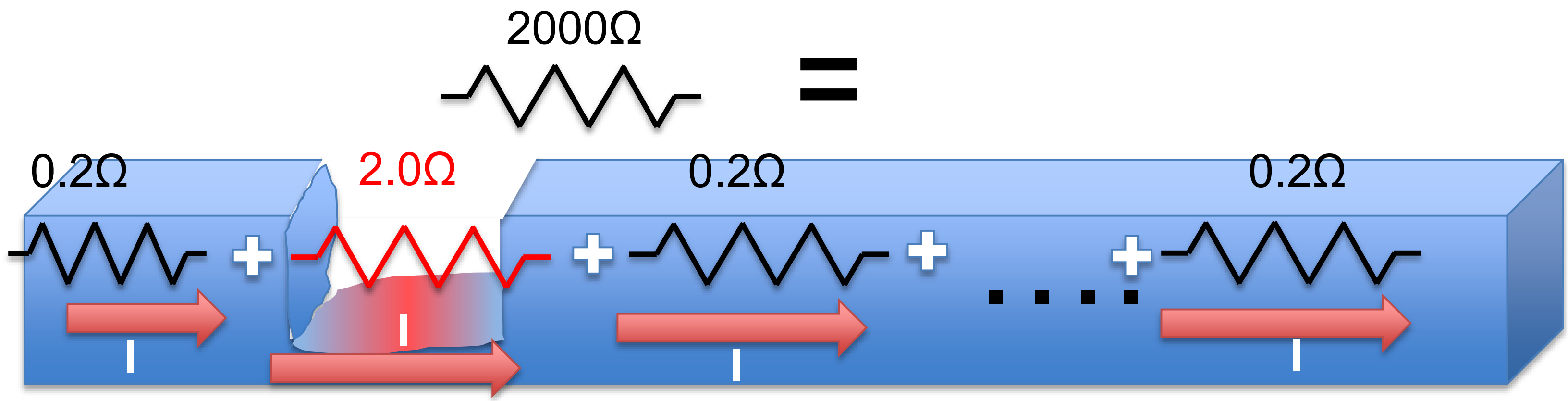


* In the case of a “Trimmed Part” the change in resistance is accounted for and the change becomes part of the final value.

A “Rat Bite” Has a Higher Resistance Due to the Smaller Cross Sectional Area

Example:
For a given Length (L) segment of resistor a 90% reduction in the Cross Sectional Area, Produces a 10x INCREASE in the resistance of the normal segment

The Same Electrical Current (I) in Amperes
Flows Through ALL Segments of this Resistor



But the POWER Dissipated in the “RAT BITE” is Higher
Because its Resistance is Larger

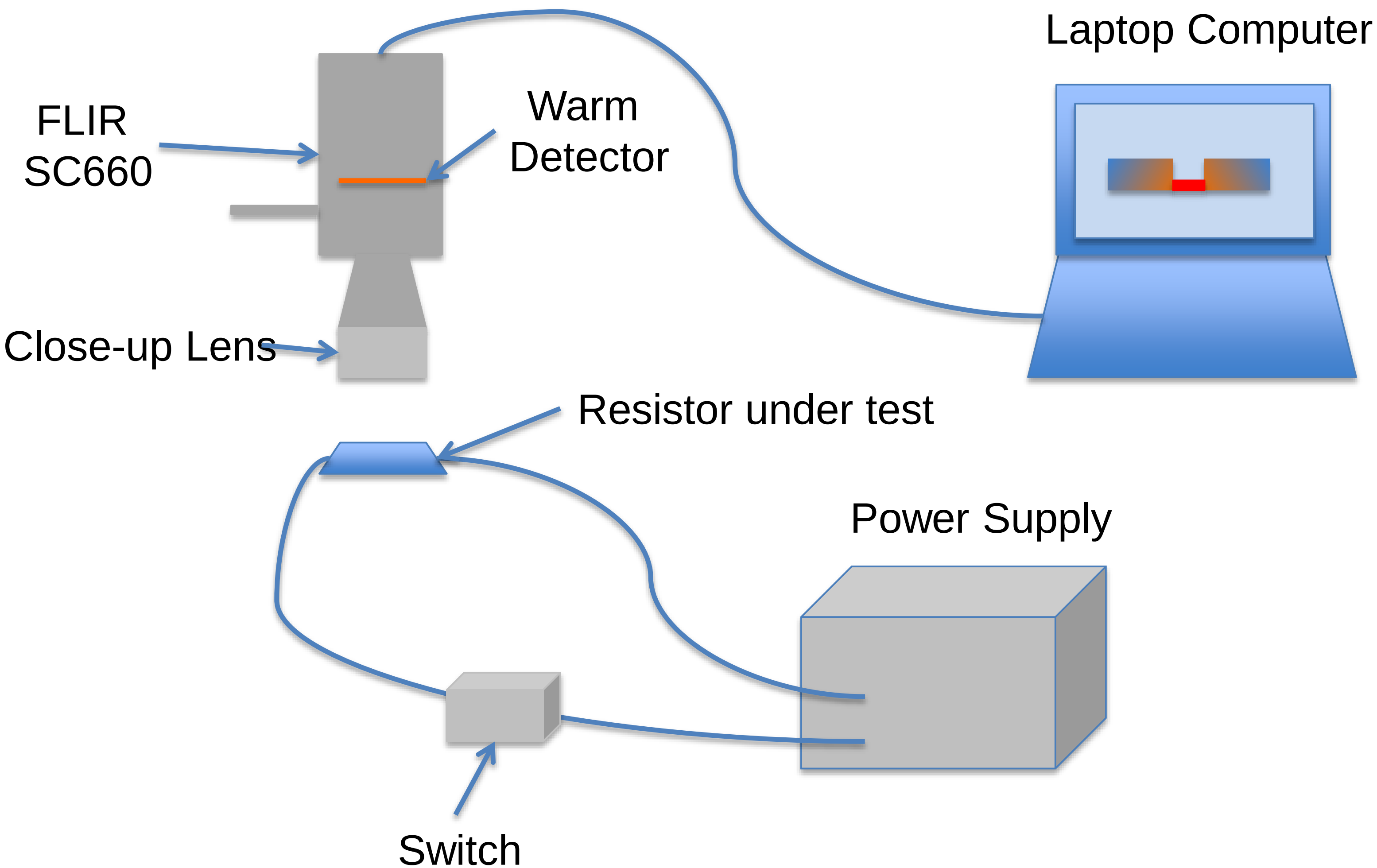
$$P = I^2 * R$$

“Rat Bites” Get Hot Because

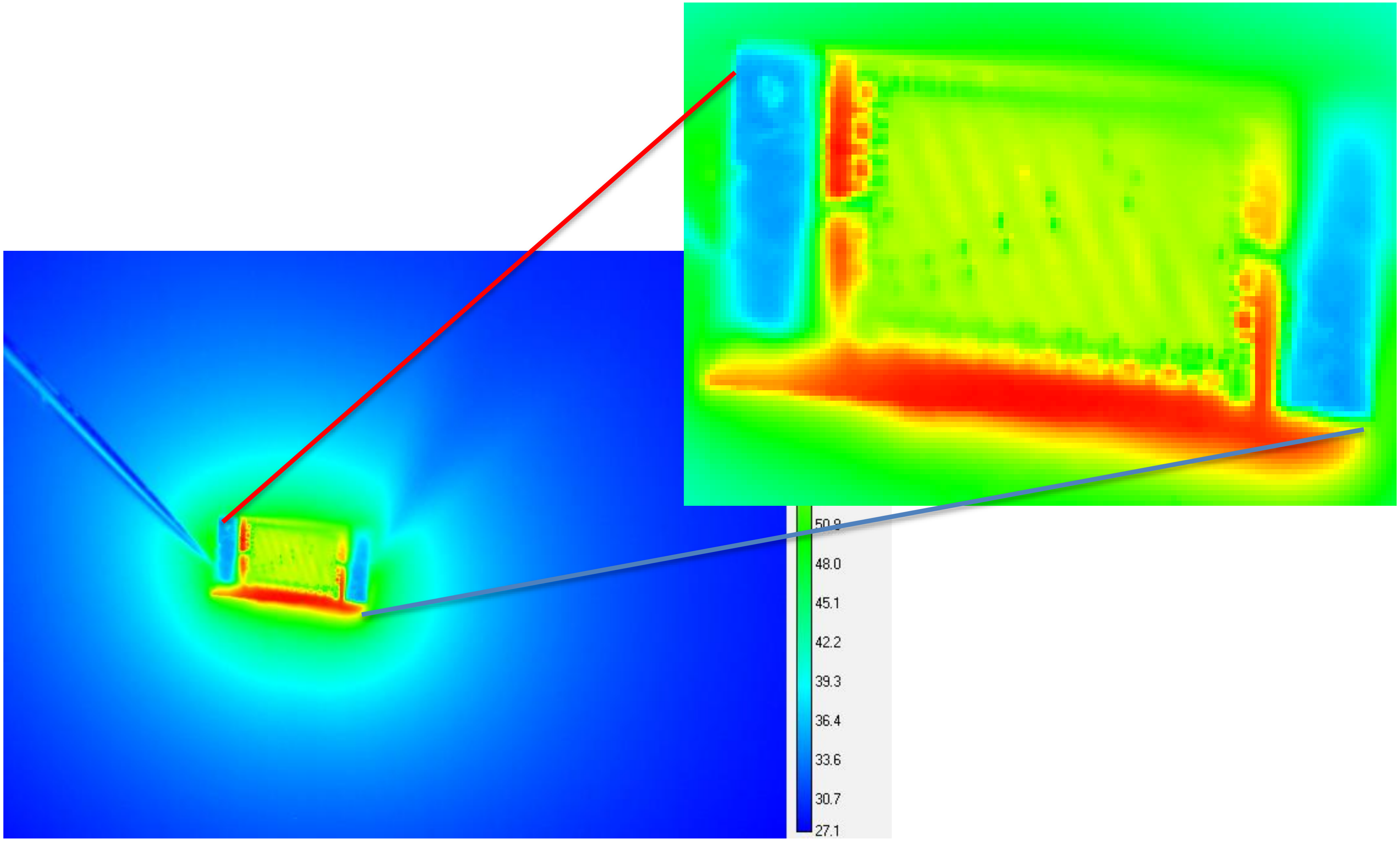
they
Dissipate MORE Power than Other Parts
of the Resistor

How hot does it get, how fast does it get hot and could it induce a failure?

Original Test Setup

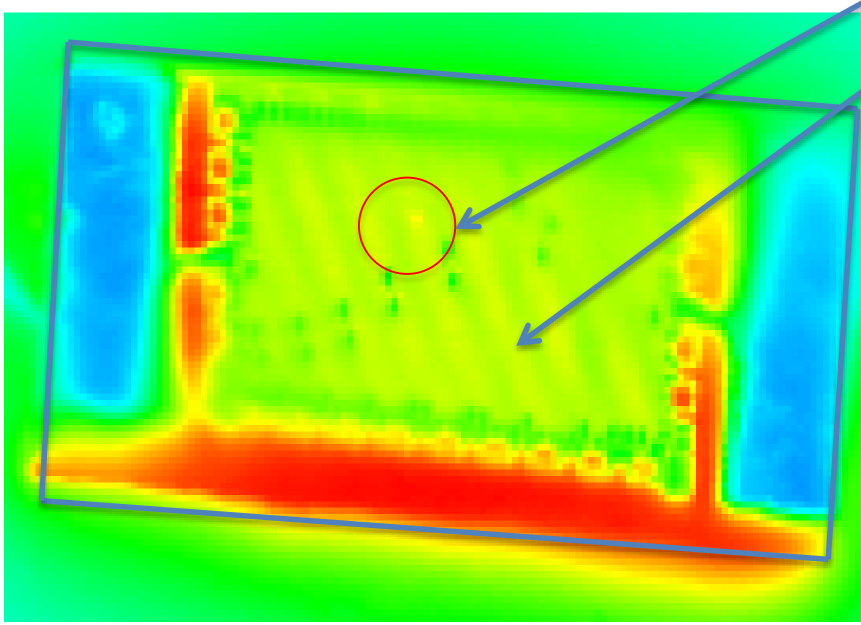


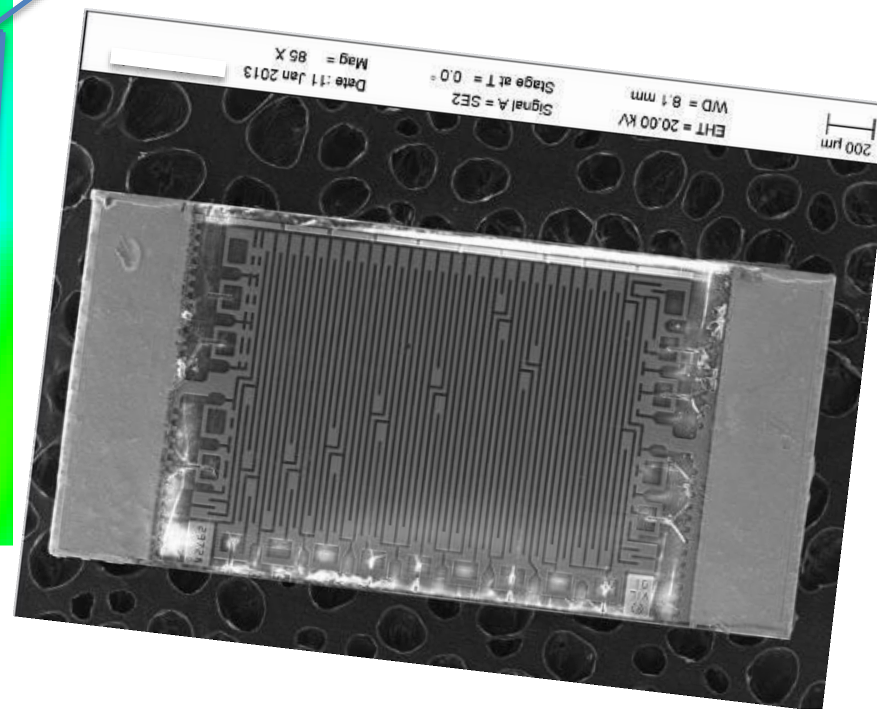
First Test Run



Items of Interest

Hot Spot
Stripes

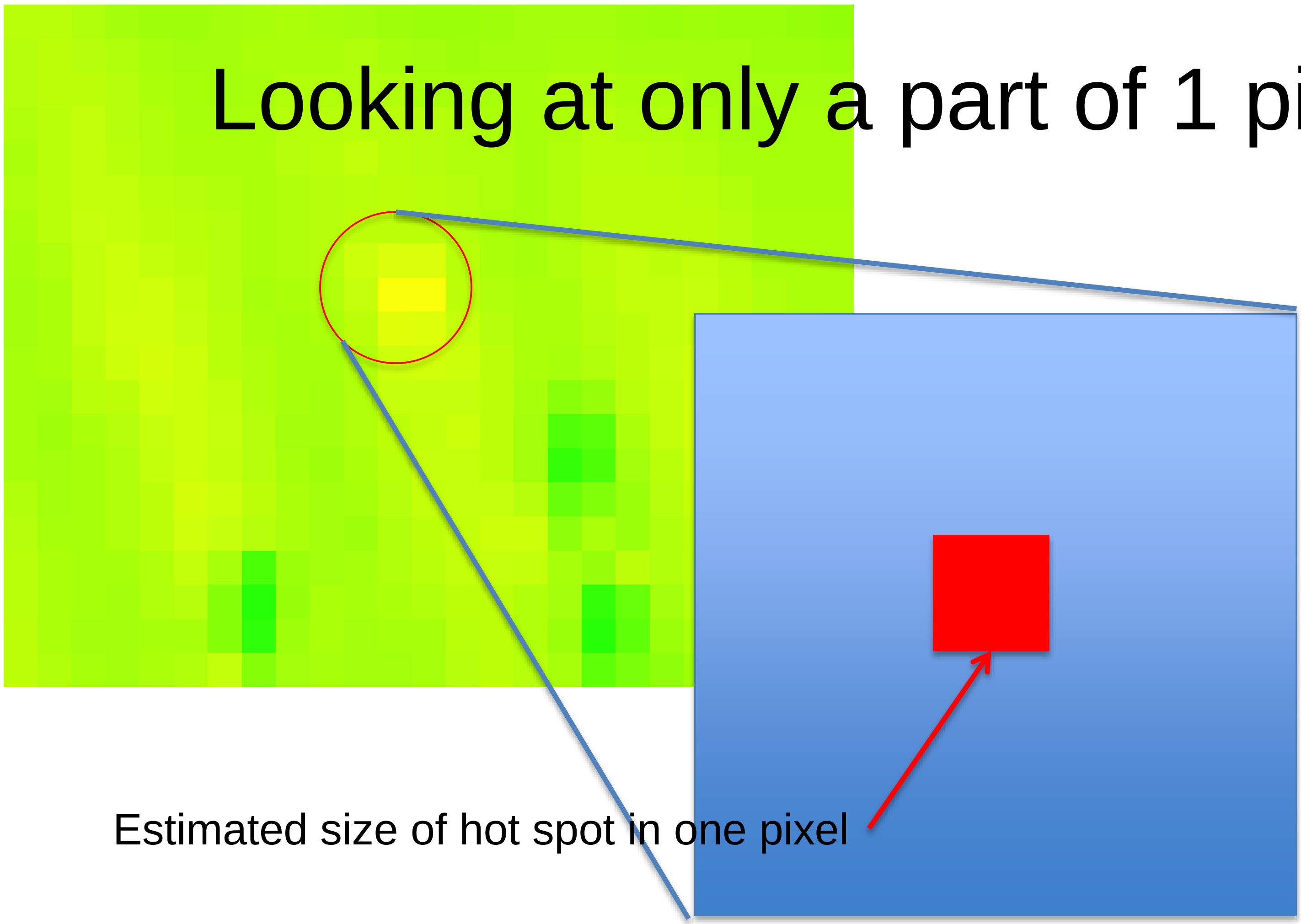




Accomplishments of First Run

- Overall we could see the resistor was getting hot.
- Temperature rise at one spot was MAYBE 2C had expected a 60C rise.
- Expected to see 2 hot spots and saw maybe only 1.
- Saw "diagonal" stripes that were unexpected.

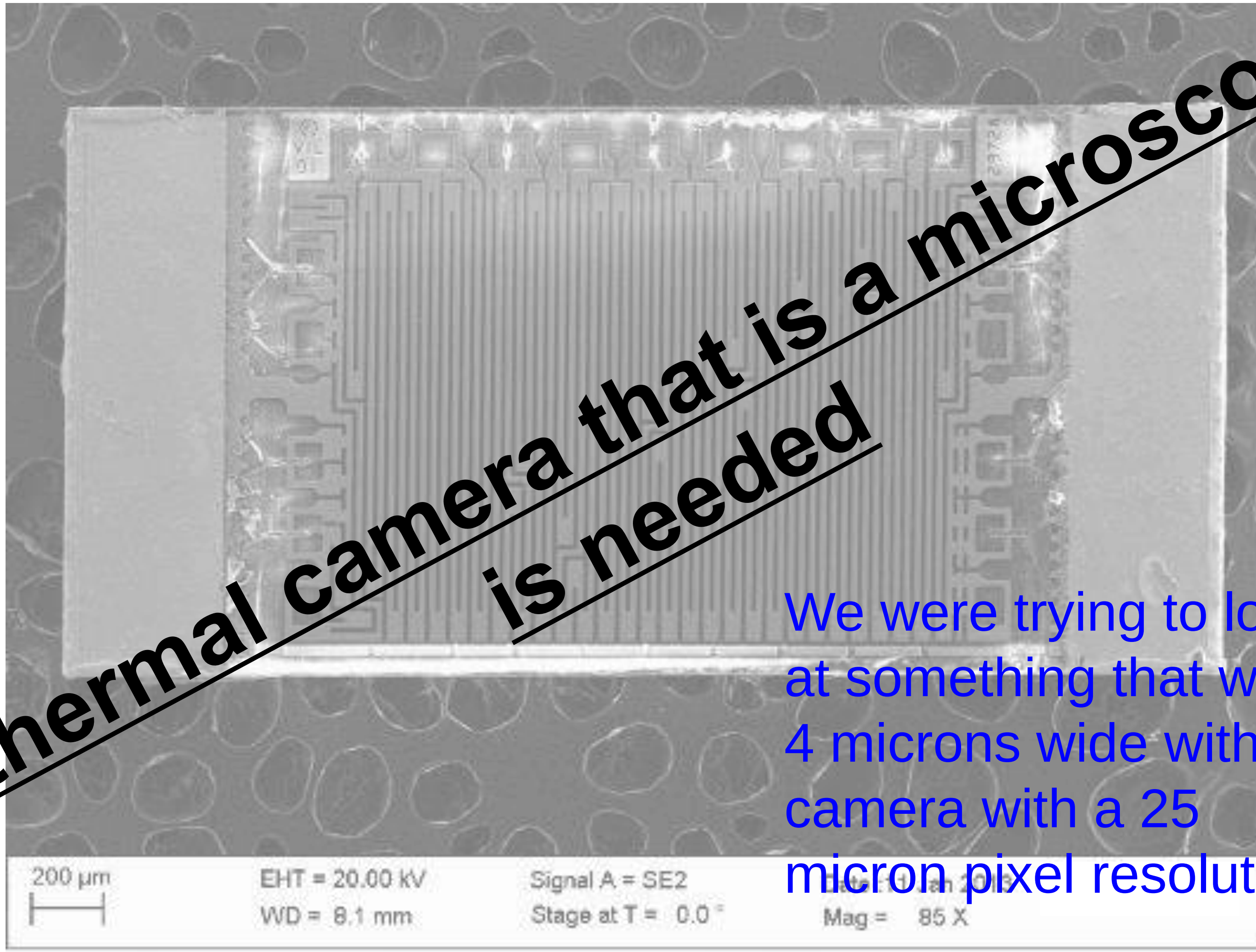
Disappointed, but What Went Right?



Disappointed, but What Went Right?

- Overall we could see the resistor was getting hot.
- With a quick calculation the expected temperature of the one pixel was about right.
  - This is hand waving at its finest
- Expected to see 2 hot spots and saw maybe only 1.
  - To be expected as the second hot spot was physically even smaller than the one we saw
- Saw diagonal stripes that were unexpected.
  - More on this later

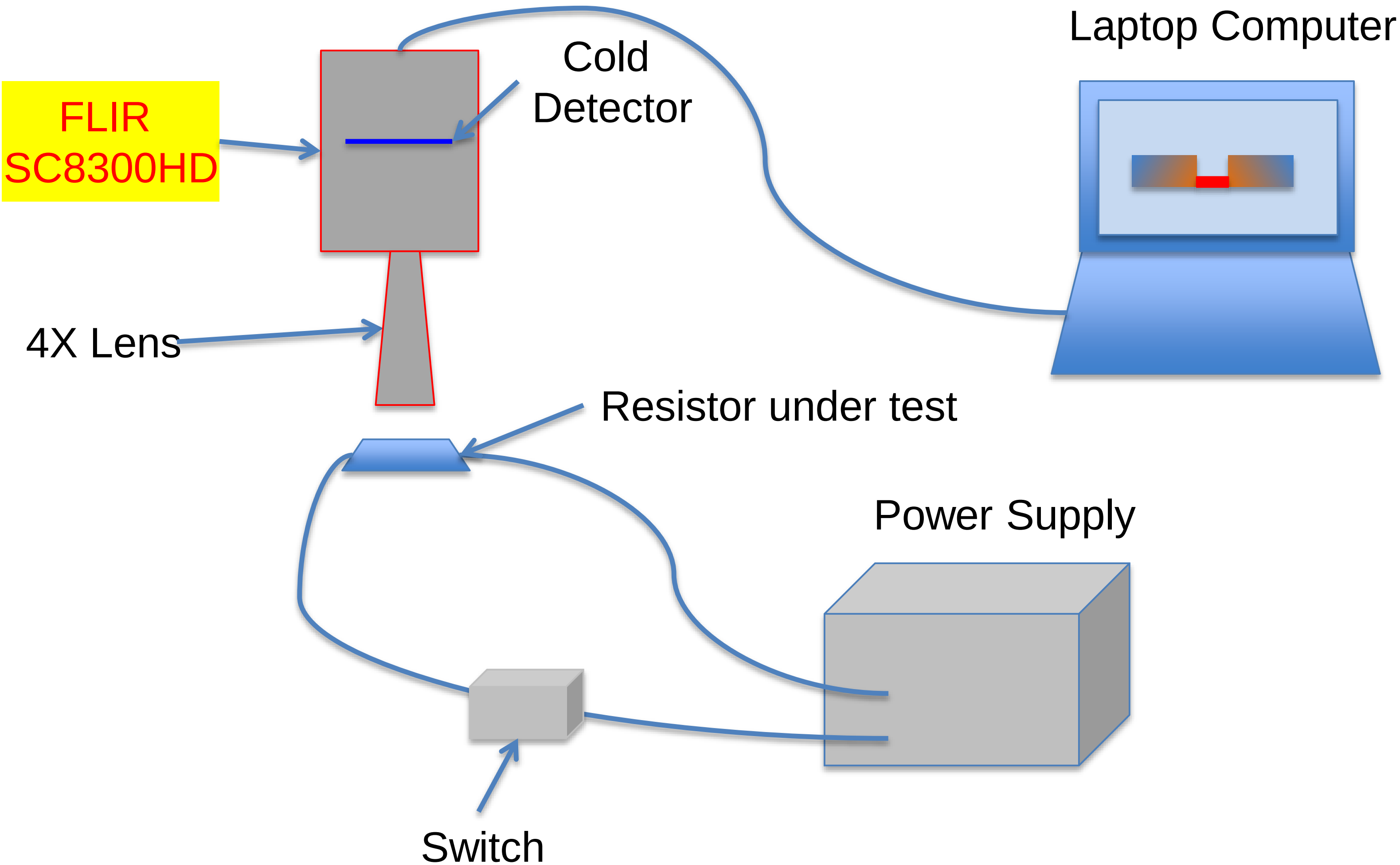
A Conclusion



A thermal camera that is a microscope is needed

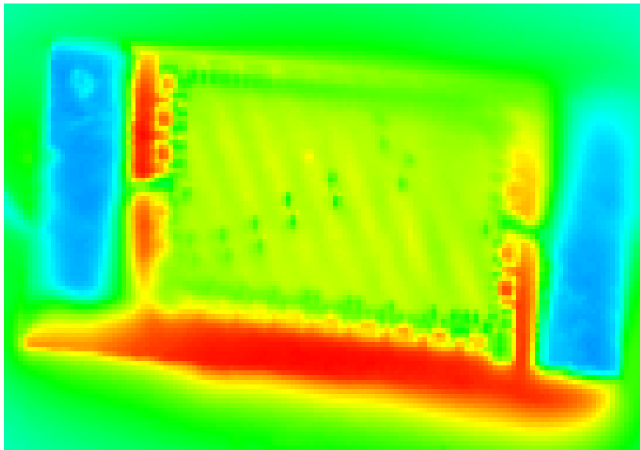
We were trying to look at something that was 4 microns wide with a camera with a 25 micron pixel resolution.

New Test Setup

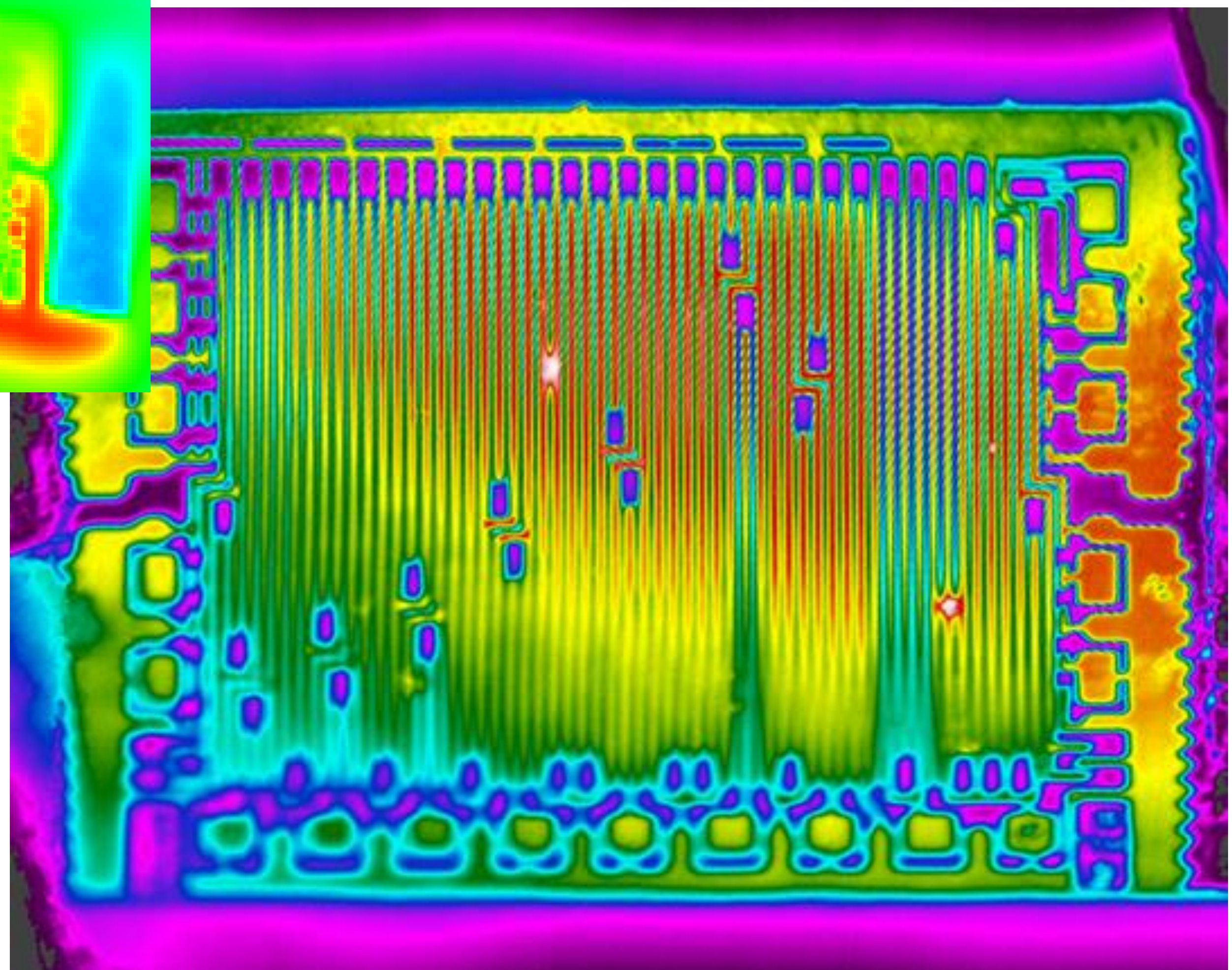


First Light

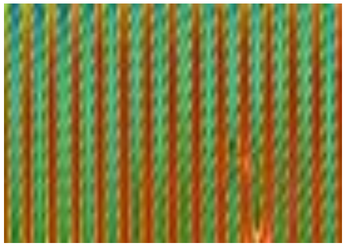
Was



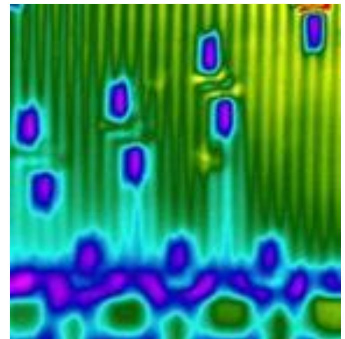
IS



Items of Interest from First Light

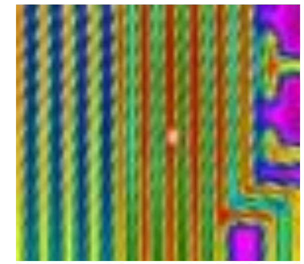


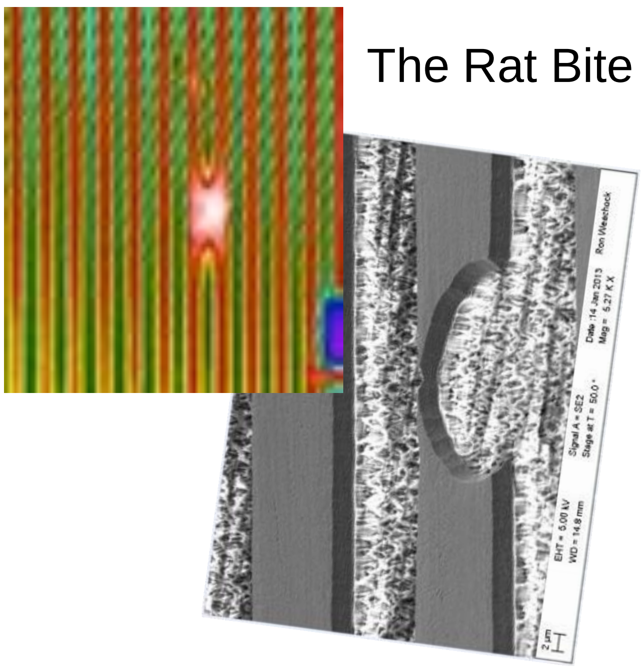
Moiré Patterns



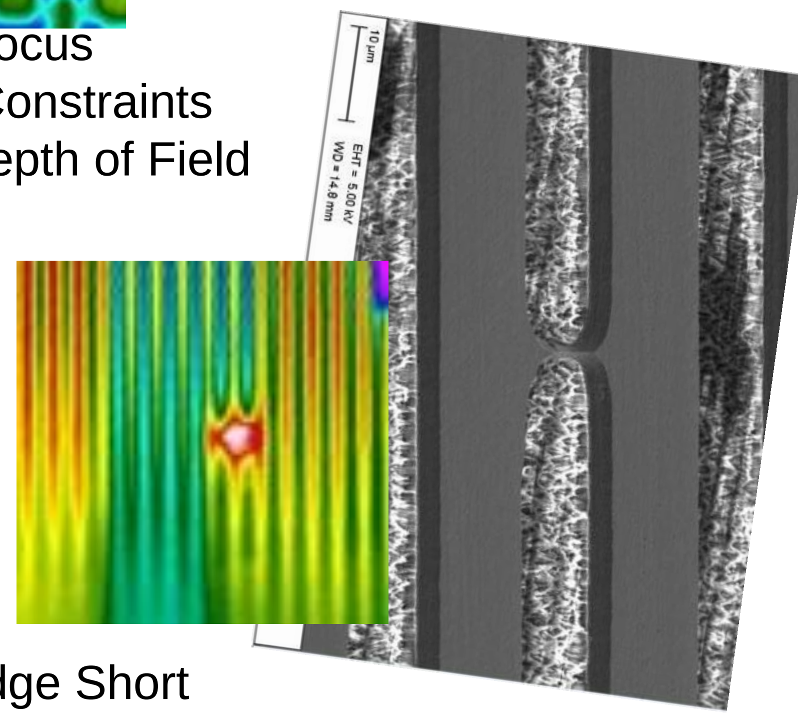
Out of Focus
Due to Time Constraints
Very Shallow Depth of Field

Dust



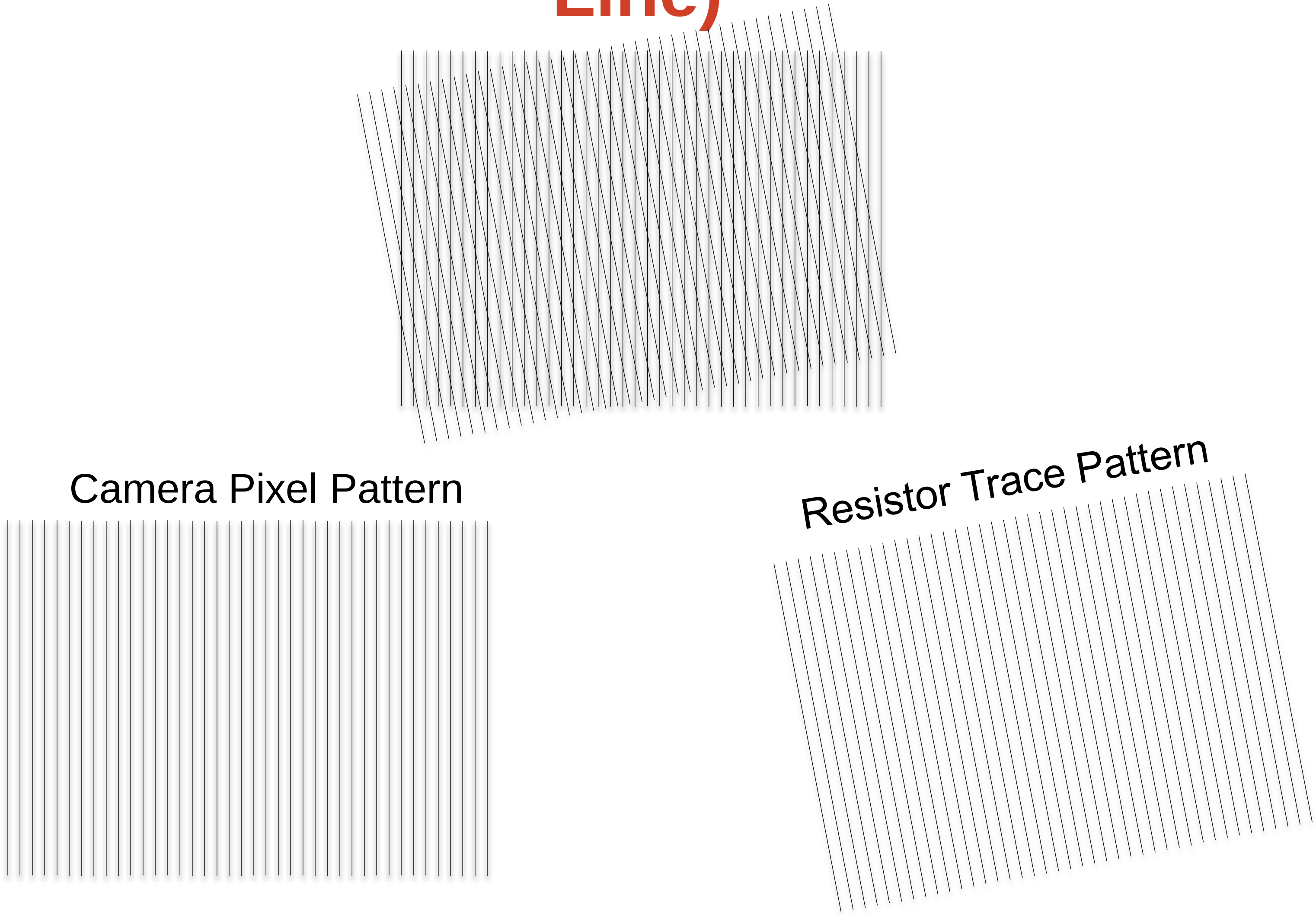


The Rat Bite

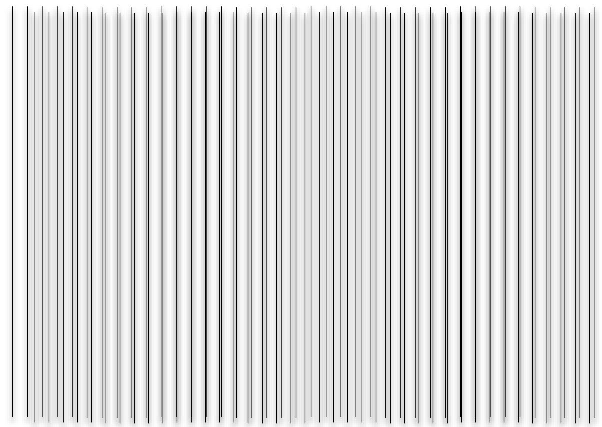


Bridge Short

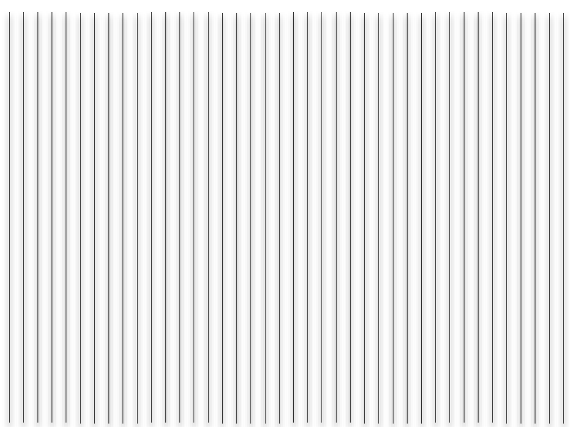
Moiré Pattern (11° Angle Fine Line)



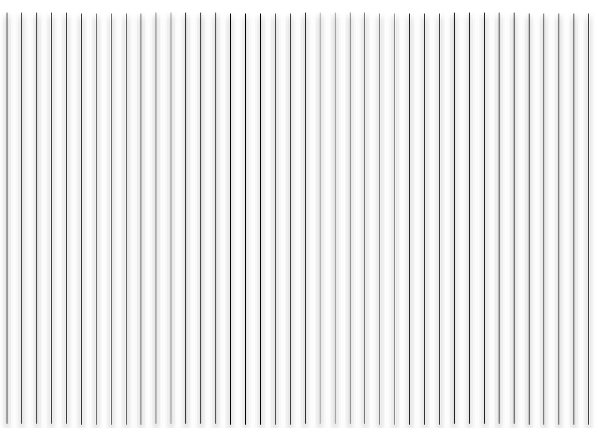
Moiré Pattern (Parallel Fine Line)



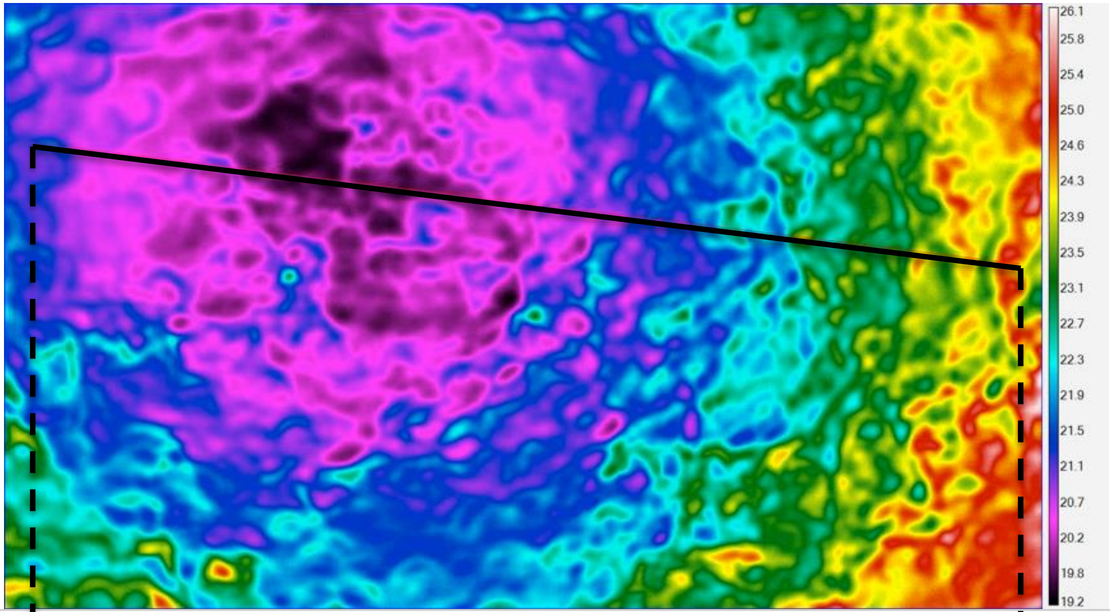
Camera Pixel Pattern

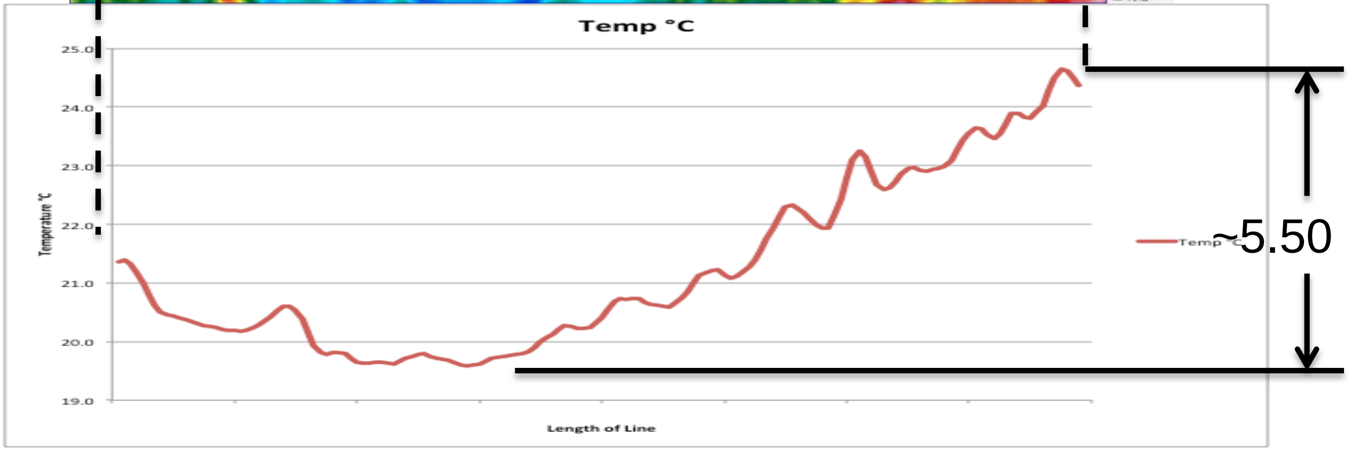


Resistor Trace Pattern



Narcissus Effect on Emissivity Measurement





Room Temp with One Emissivity

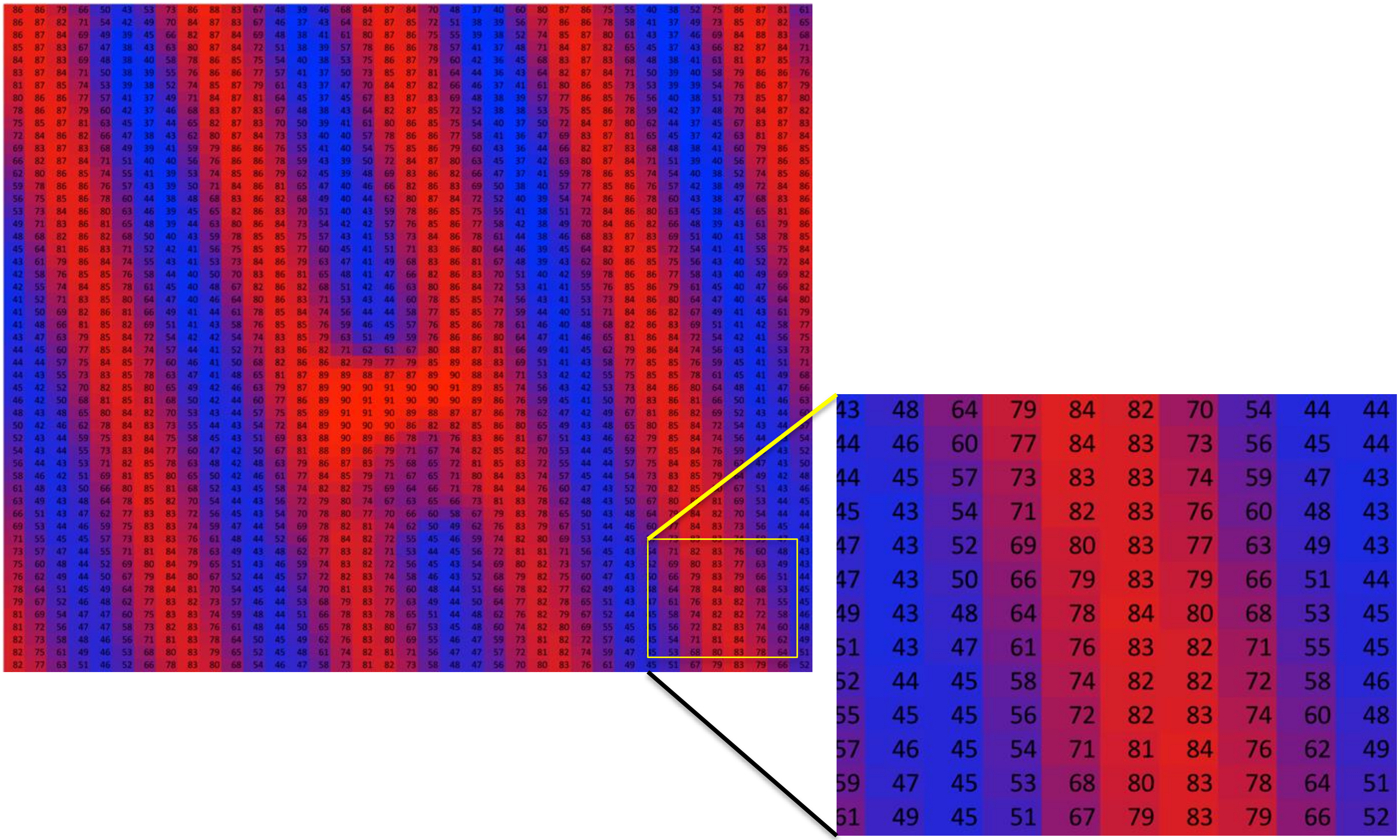
21.4	19.3	14.5	10.8	10.2	14.0	19.0	21.3	21.5	20.1	15.8
21.4	19.7	15.6	11.2	10.0	13.0	18.4	21.1	21.5	[illegible]	[illegible]
21.4	20.1	16.3	11.7	10.0	12.4	17.7	20.9	21.6	[illegible]	[illegible]
21.5	20.4	16.9	12.2	10.2	11.7	16.9	20.6	21.6	[illegible]	[illegible]
21.5	20.7	17.6	12.8	10.4	11.3	16.1	20.1	21.5	[illegible]	[illegible]
21.5	20.9	18.1	13.5	10.4	11.0	15.3	19.7	21.5	21.3	19.1
21.5	21.1	18.8	14.2	11.0	10.6	14.6	19.3	21.2	21.4	19.5
21.3	21.2	19.2	15.0	11.3	10.5	13.7	18.7	21.1	21.4	19.9
21.2	21.3	19.7	15.7	11.7	10.6	13.1	18.1	20.9	21.5	20.4
21.0	21.4	20.0	16.4	12.3	10.5	12.7	17.5	20.7	21.5	20.6
20.8	21.4	20.4	17.1	12.8	10.7	12.2	16.9	20.5	21.5	20.8
20.5	21.4	20.6	17.7	13.3	10.9	11.8	16.2	20.2	21.5	21.1
20.1	21.3	20.9	18.4	13.9	11.2	11.4	15.4	19.8	21.3	21.3
19.8	21.2	21.1	19.0	14.8	11.5	11.2	14.9	19.5	21.3	21.4
19.1	21.2	21.3	19.5	15.5	12.1	11.6	14.8	19.3	21.2	21.4
18.7	21.0	21.3	20.0	16.6	13.4	13.0	15.5	19.5	21.4	21.5
18.2	20.8	21.4	20.6	18.4	16.7	16.3	17.6	20.2	21.7	21.7
17.4	20.4	21.5	21.4	20.8	20.3	20.0	20.2	21.2	22.0	21.9
16.8	20.3	21.6	22.0	22.0	22.0	21.8	21.8	22.0	22.2	21.9

Actual Temp's 23C

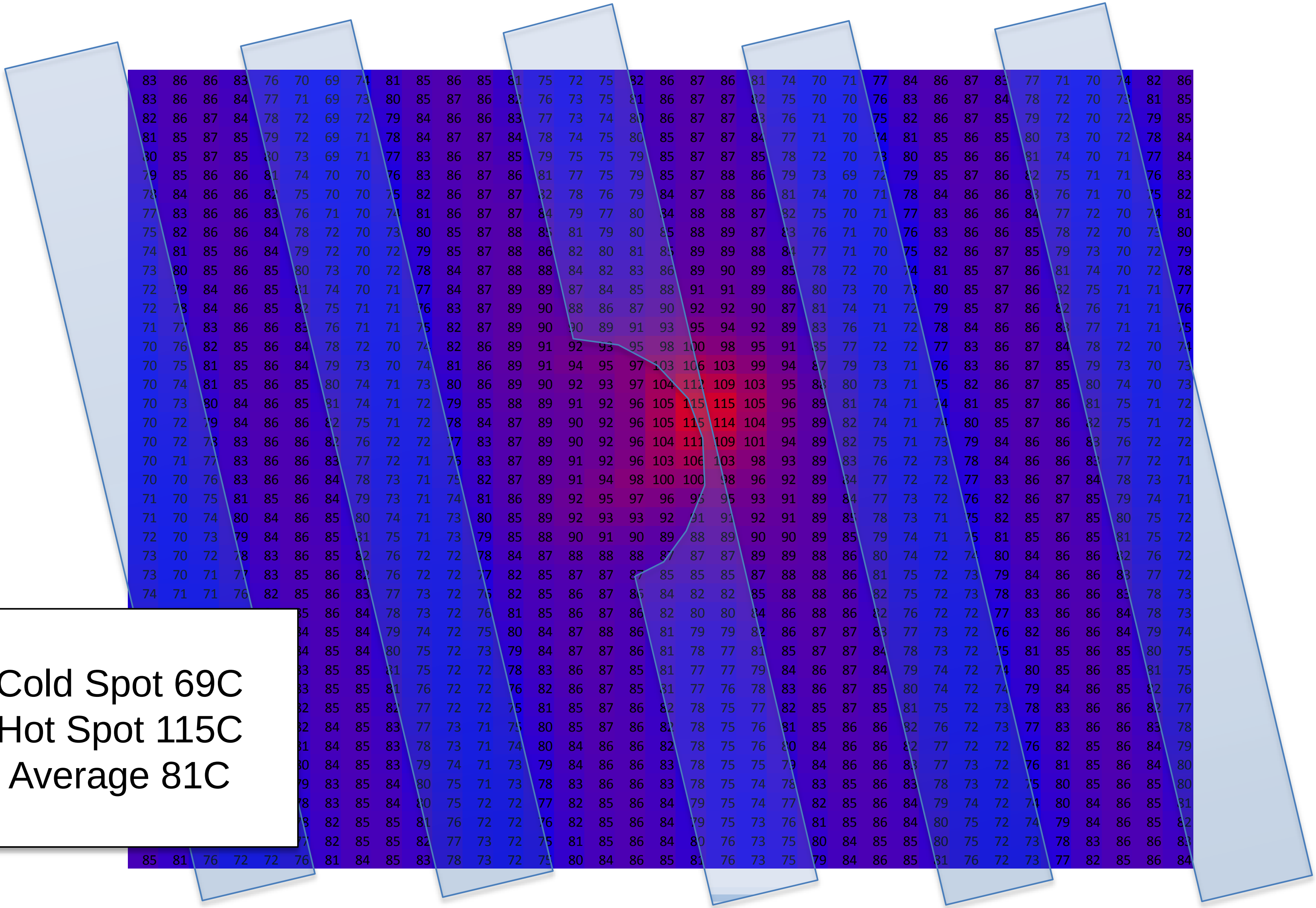
10.5C

21.7C

Emissivity Map

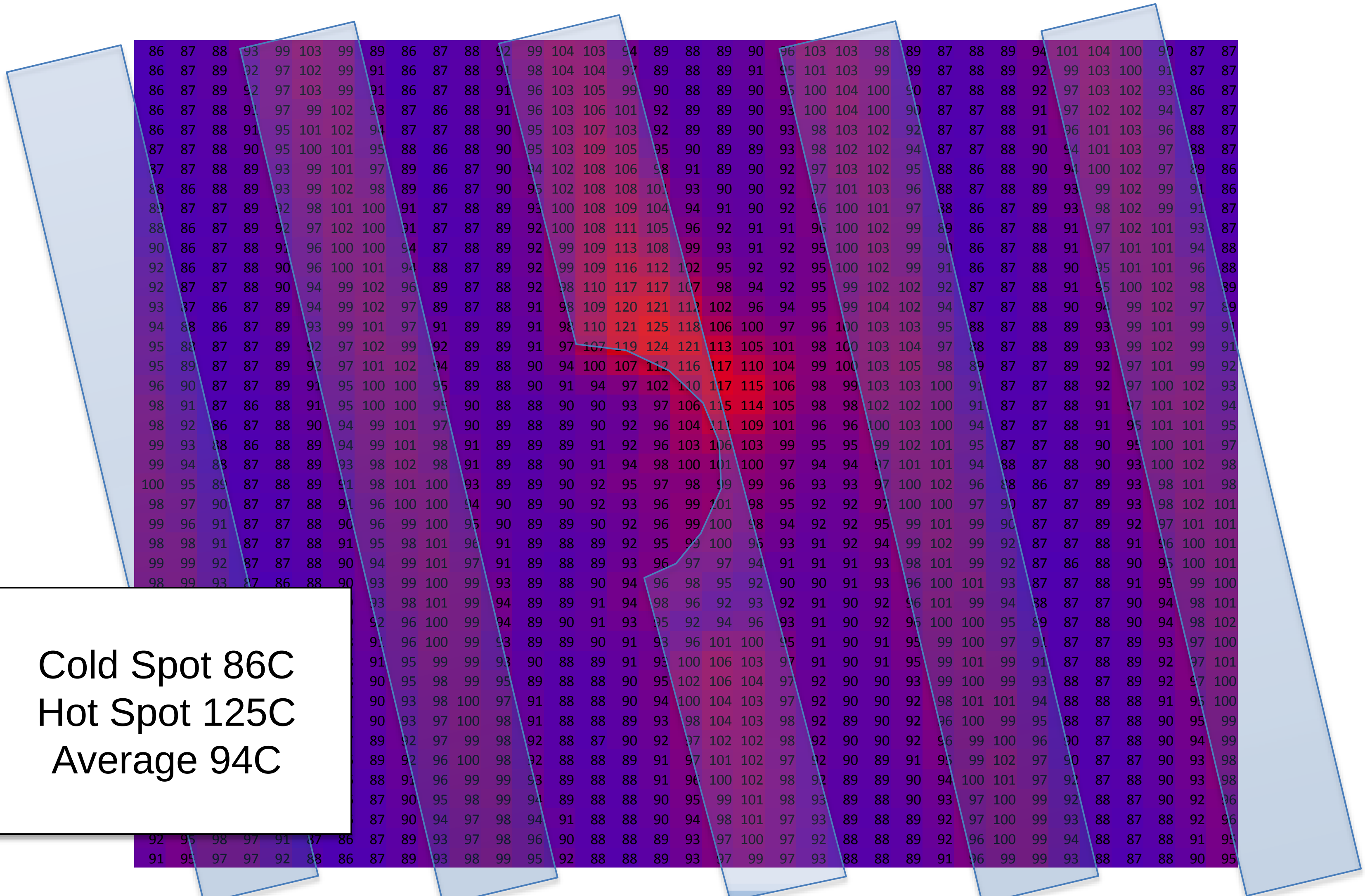


Rat Bite at One Emissivity



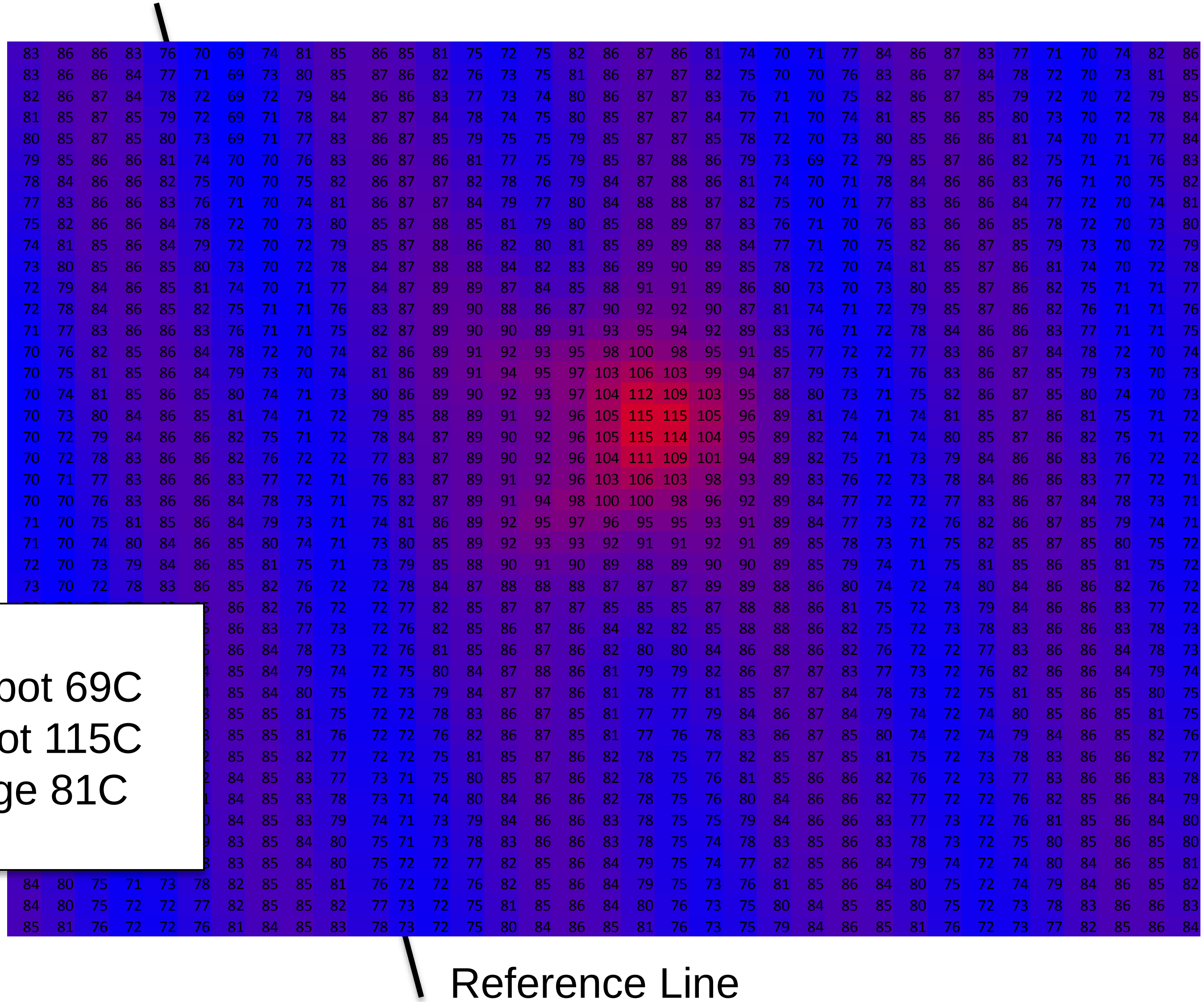
Cold Spot 69C
Hot Spot 115C
Average 81C

Hot Spot Adjusted Emissivity



Cold Spot 86C
Hot Spot 125C
Average 94C

Rat Bite at One Emissivity



Cold Spot 69C
Hot Spot 115C
Average 81C

Reference Line

Hot Spot Adjusted Emissivity

86	87	88	93	99	103	99	89	86	87	88	92	99	104	103	94	89	88	89	90	96	103	103	98	89	87	88	89	94	101	104	100	90	87	87
86	87	89	92	97	102	99	91	86	87	88	91	98	104	104	97	89	88	89	91	95	101	103	99	89	87	88	89	92	99	103	100	91	87	87
86	87	89	92	97	103	99	91	86	87	88	91	96	103	105	99	90	88	89	90	95	100	104	100	90	87	88	88	92	97	103	102	93	86	87
86	87	88	91	97	99	102	93	87	86	88	91	96	103	106	101	92	89	89	90	93	100	104	100	90	87	87	88	91	97	102	102	94	87	87
86	87	88	91	95	101	102	94	87	87	88	90	95	103	107	103	92	89	89	90	93	98	103	102	92	87	87	88	91	96	101	103	96	88	87
87	87	88	90	95	100	101	95	88	86	88	90	95	103	109	105	95	90	89	89	93	98	102	102	94	87	87	88	90	94	101	103	97	88	87
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88	86	88	89	93	99	102	98	89	86	87	90	95	102	108	108	101	93	90	90	92	97	101	103	96	88	87	88	89	93	99	102	99	91	86
89	87	87	89	92	98	101	100	91	87	88	89	93	100	108	109	104	94	91	90	92	96	100	101	97	88	86	87	89	93	98	102	99	91	87
88	86	87	89	92	97	102	100	91	87	87	89	92	100	108	111	105	96	92	91	91	96	100	102	99	89	86	87	88	91	97	102	101	93	87
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92	87	87	88	90	94	99	102	96	89	87	88	92	98	110	117	117	107	98	94	92	95	99	102	102	92	87	87	88	91	95	100	102	98	89
93	87	86	87	89	94	99	102	97	89	87	88	91	98	109	120	121	112	102	96	94	95	99	104	102	94	87	87	88	90	94	99	102	97	89
94	88	86	87	89	93	99	101	97	91	89	89	91	98	110	121	125	118	106	100	97	96	100	103	103	95	88	87	88	89	93	99	101	99	91
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95	89	87	87	89	92	97	101	102	94	89	88	90	94	100	107	112	116	117	110	104	99	100	103	105	98	89	87	87	89	92	97	101	99	92
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						89	92	96	100	99	94	89	90	91	93	95	92	94	96	93	91	90	92	96	100	100	95	89	87	88	90	94	98	102
						88	91	96	100	99	93	89	89	90	91	93	96	101	100	95	91	90	91	95	99	100	97	91	87	87	89	93	97	100
						88	91	95	99	99	93	90	88	89	91	93	100	106	103	97	91	90	91	95	99	101	99	91	87	88	89	92	97	101
						88	90	95	98	99	95	89	88	88	90	95	102	106	104	97	92	90	90	93	99	100	99	93	88	87	89	92	97	100
						87	90	93	98	100	97	91	88	88	90	94	100	104	103	97	92	90	90	92	98	101	101	94	88	88	88	91	95	100
						87	90	93	97	100	98	91	88	88	89	93	98	104	103	98	92	89	90	92	96	100	99	95	88	87	88	90	95	99
						87	89	92	97	99	98	92	88	87	90	92	97	102	102	98	92	90	90	92	96	99	100	96	90	87	88	90	94	99
						86	89	92	96	100	98	92	88	88	89	91	97	101	102	97	92	90	89	91	95	99	102	97	90	87	87	90	93	98
						86	88	91	96	99	99	93	89	88	88	91	96	100	102	98	92	89	89	90	94	100	101	97	92	87	88	90	93	98
						86	87	90	95	98	99	94	89	88	88	90	95	99	101	98	93	89	88	90	93	97	100	99	92	88	87	90	92	96
91	96	99	96	90	87	86	87	90	94	97	98	94	91	88	88	90	94	98	101	97	93	89	88	89	92	97	100	99	93	88	87	88	92	96
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91	95	97	97	92	88	86	87	89	93	98	99	95	92	88	88	89	93	97	99	97	93	88	88	89	91	96	99	99	93	88	87	88	90	95

Cold Spot 86C
Hot Spot 125C
Average 94C

Reference Line

Lesson Learned

Because of the very small size of the part the trace internal to the resistor heats up quickly and cools off quickly.

Thermal cycling is quick, and testing with many cycles is beneficial

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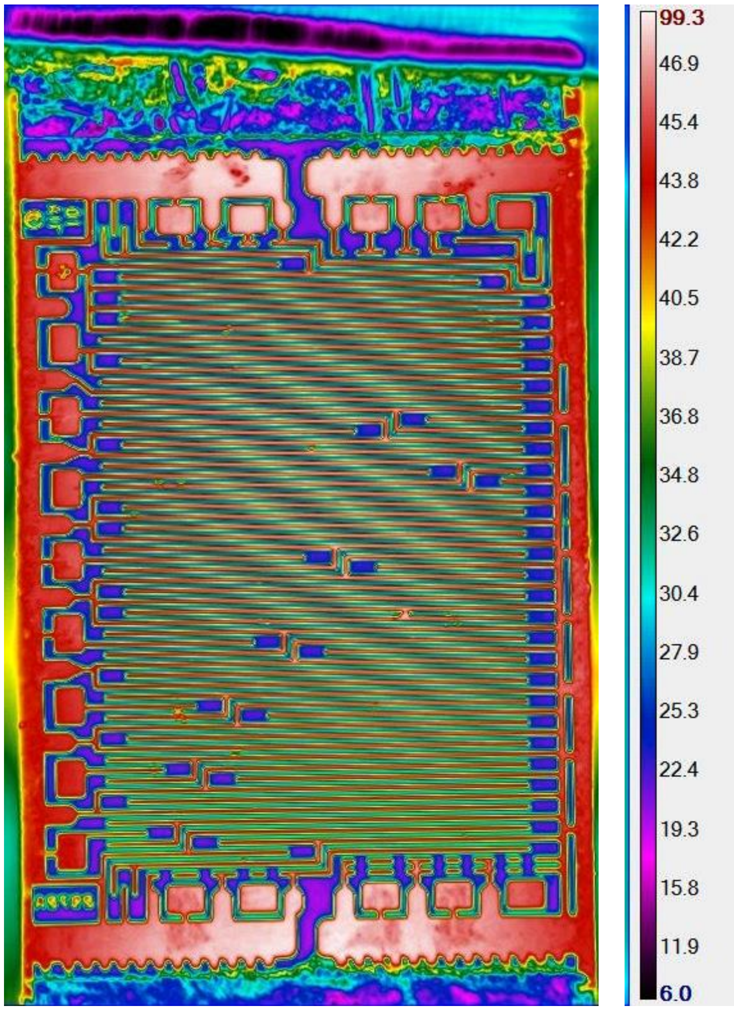
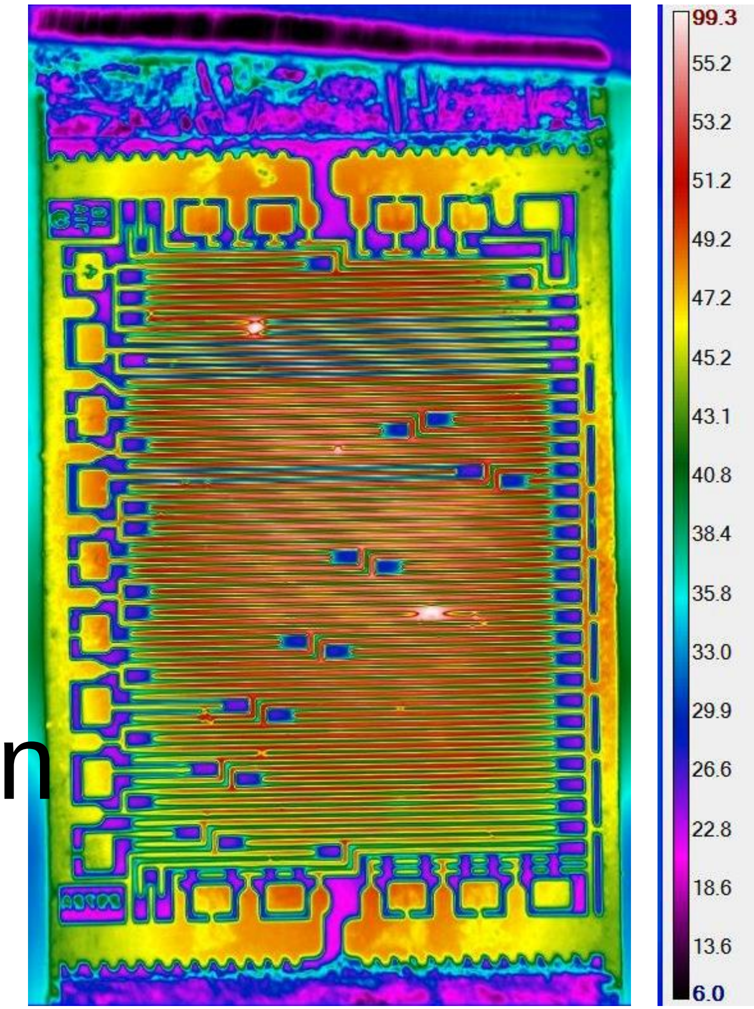
Pulse Test

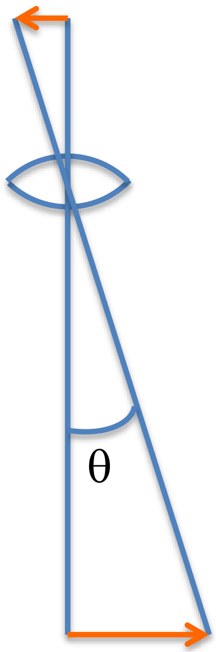


Off

On

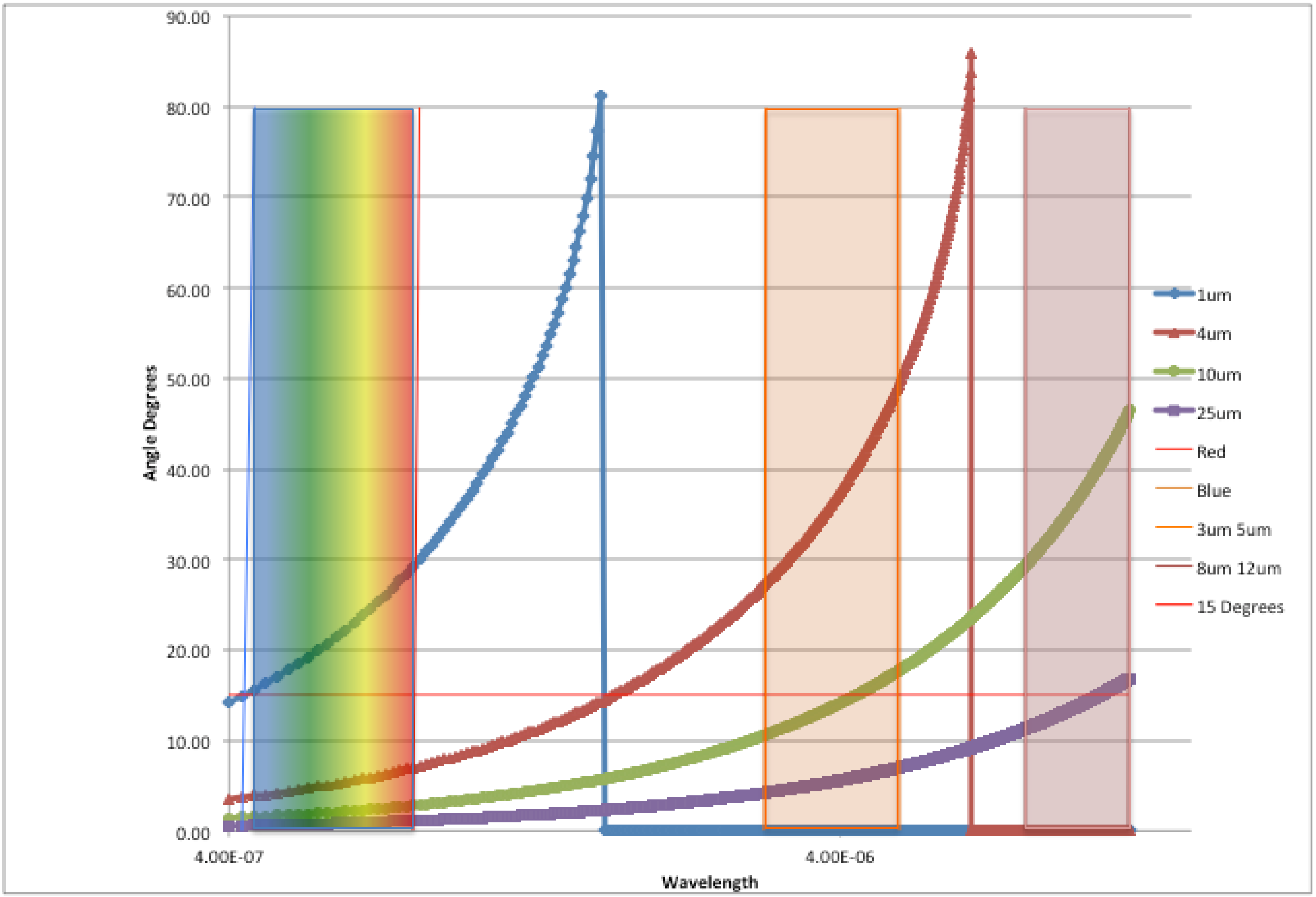


Resolution (r)

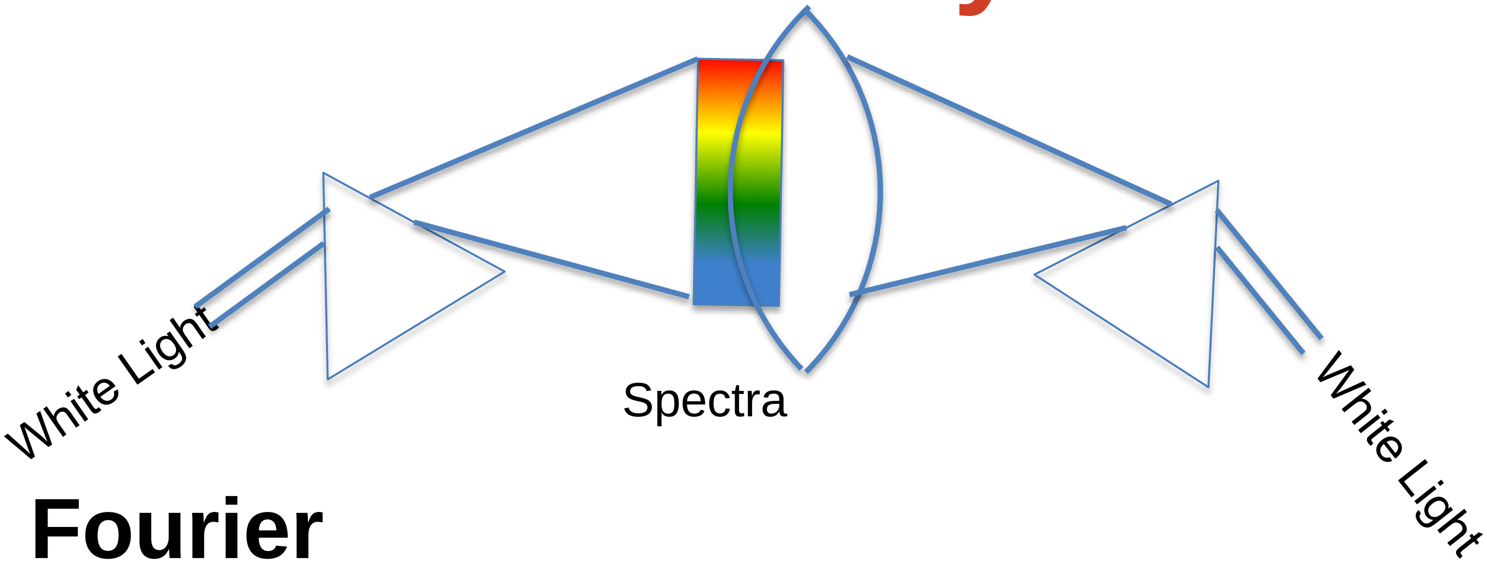


$$\mathbf{r} = \frac{1.22\lambda}{2n \text{ Sin } \theta}$$

Wavelength vs Angle

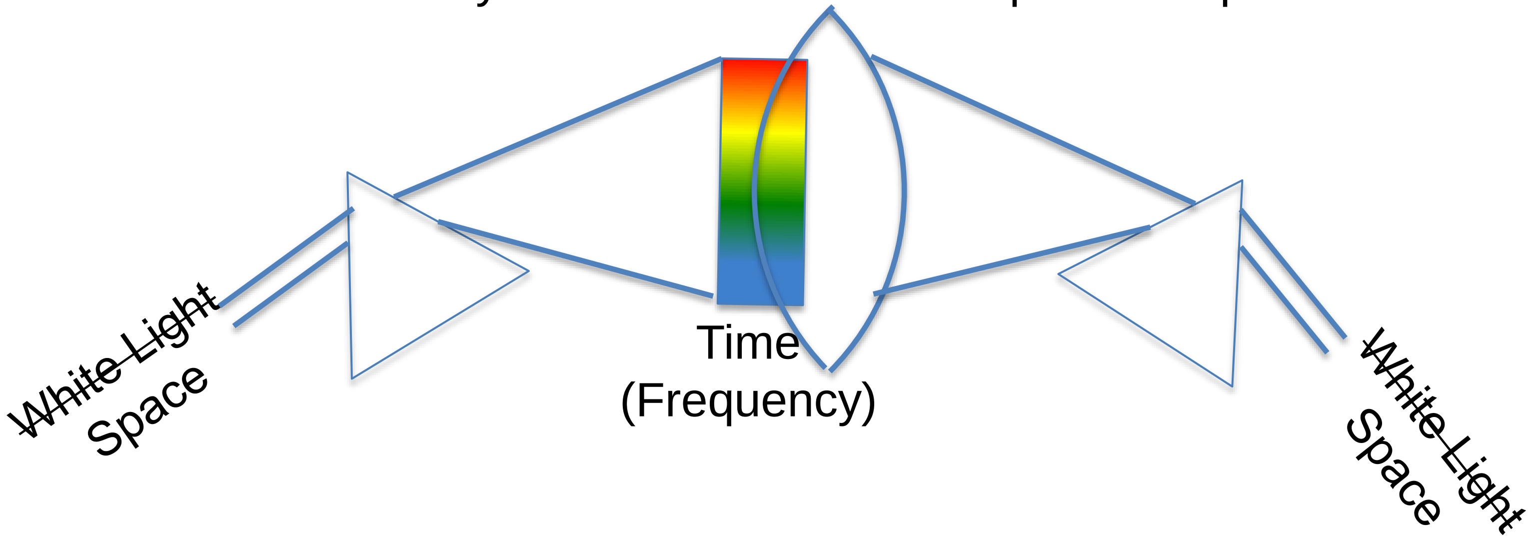


Newtonian Physics

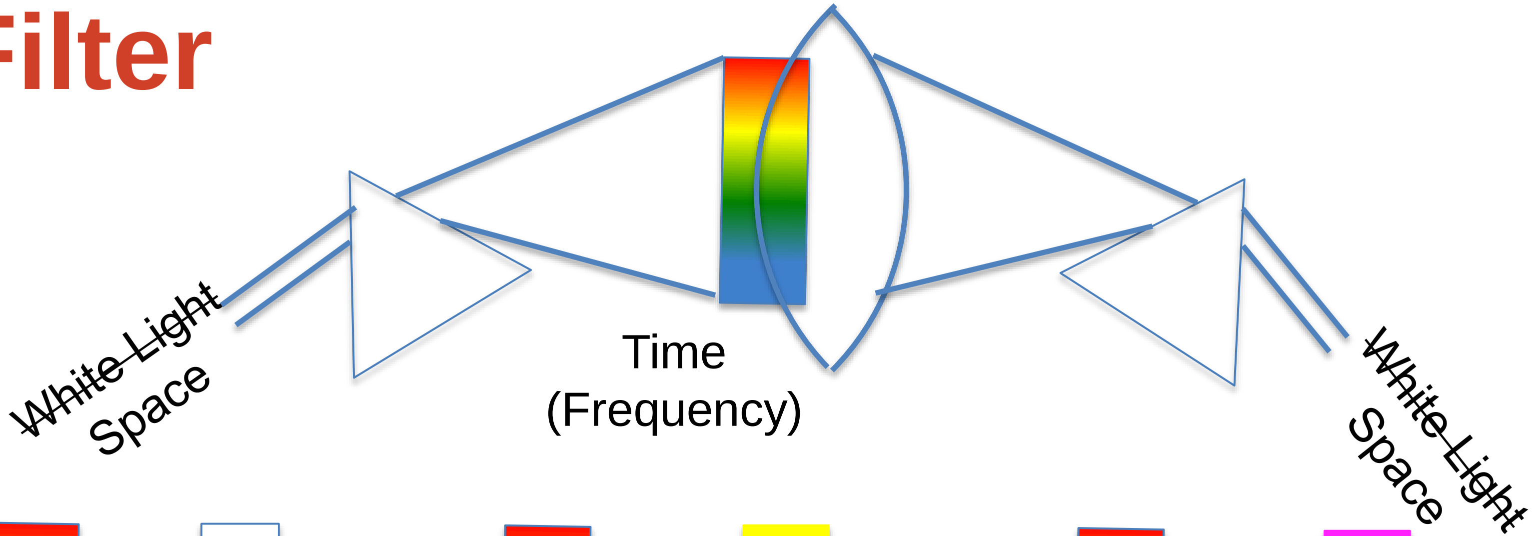


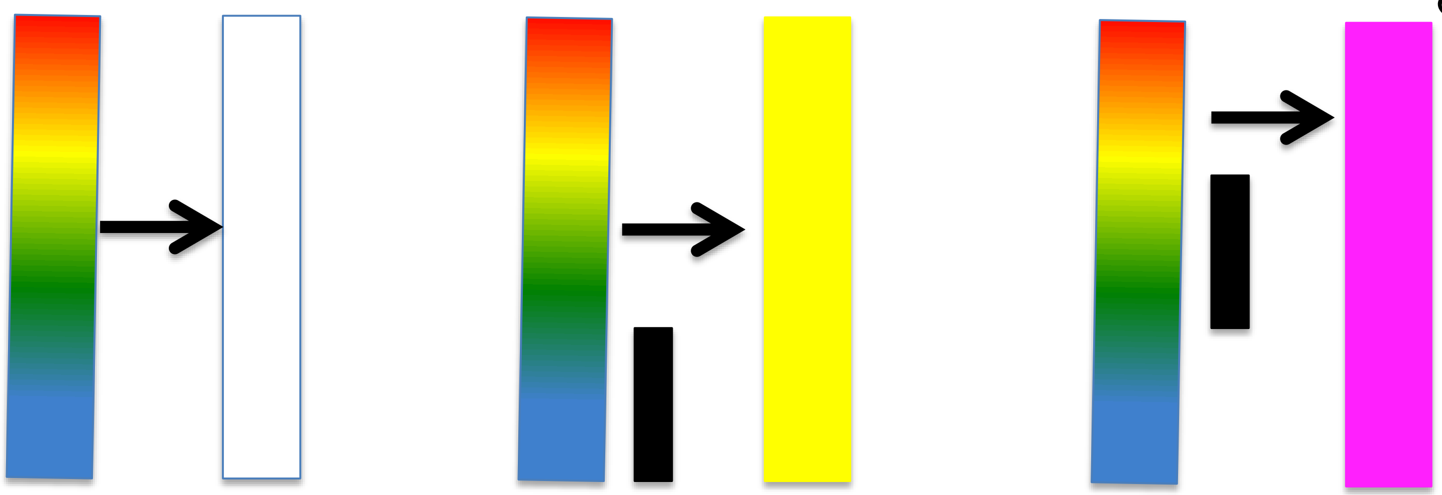
<u>Fourier</u>

Looks at the analysis between Time and Space of a periodic function



Use of Fourier Transform as a Filter





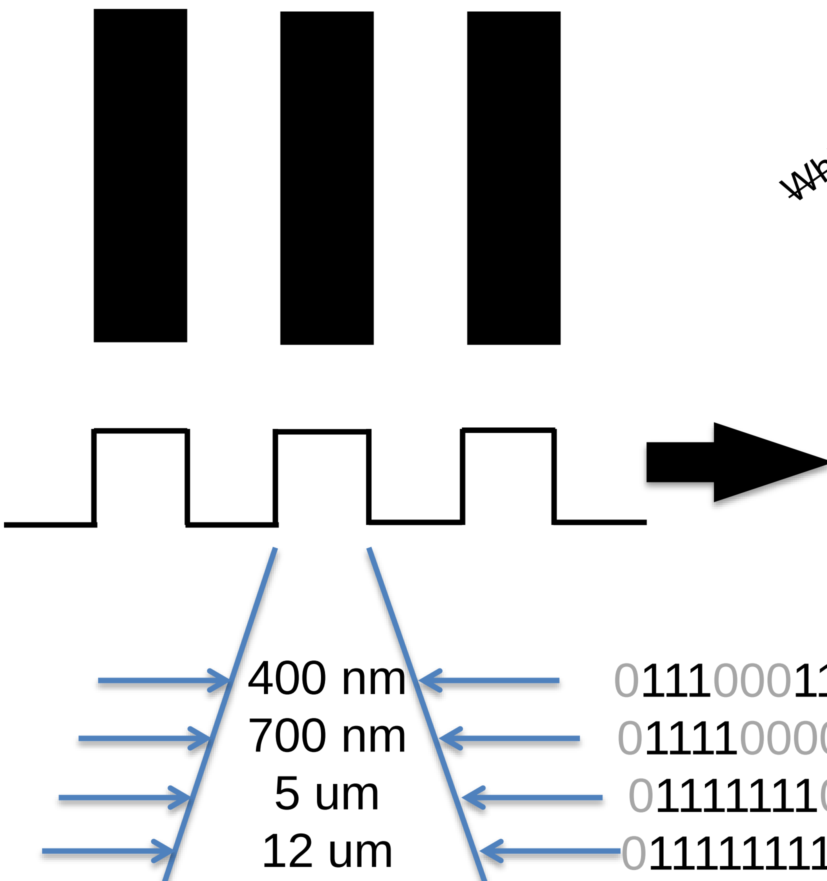
Spectra No Blocking
White

Spectra Blocking Blue
Yellow

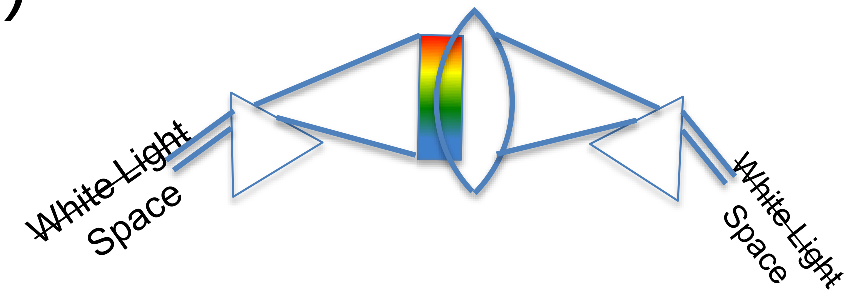
Spectra Blocking Green
Magenta

Resolution of Periodic Signal (Lines)

Line Width (space)



0111111000000111111000001



01110001110001110001110

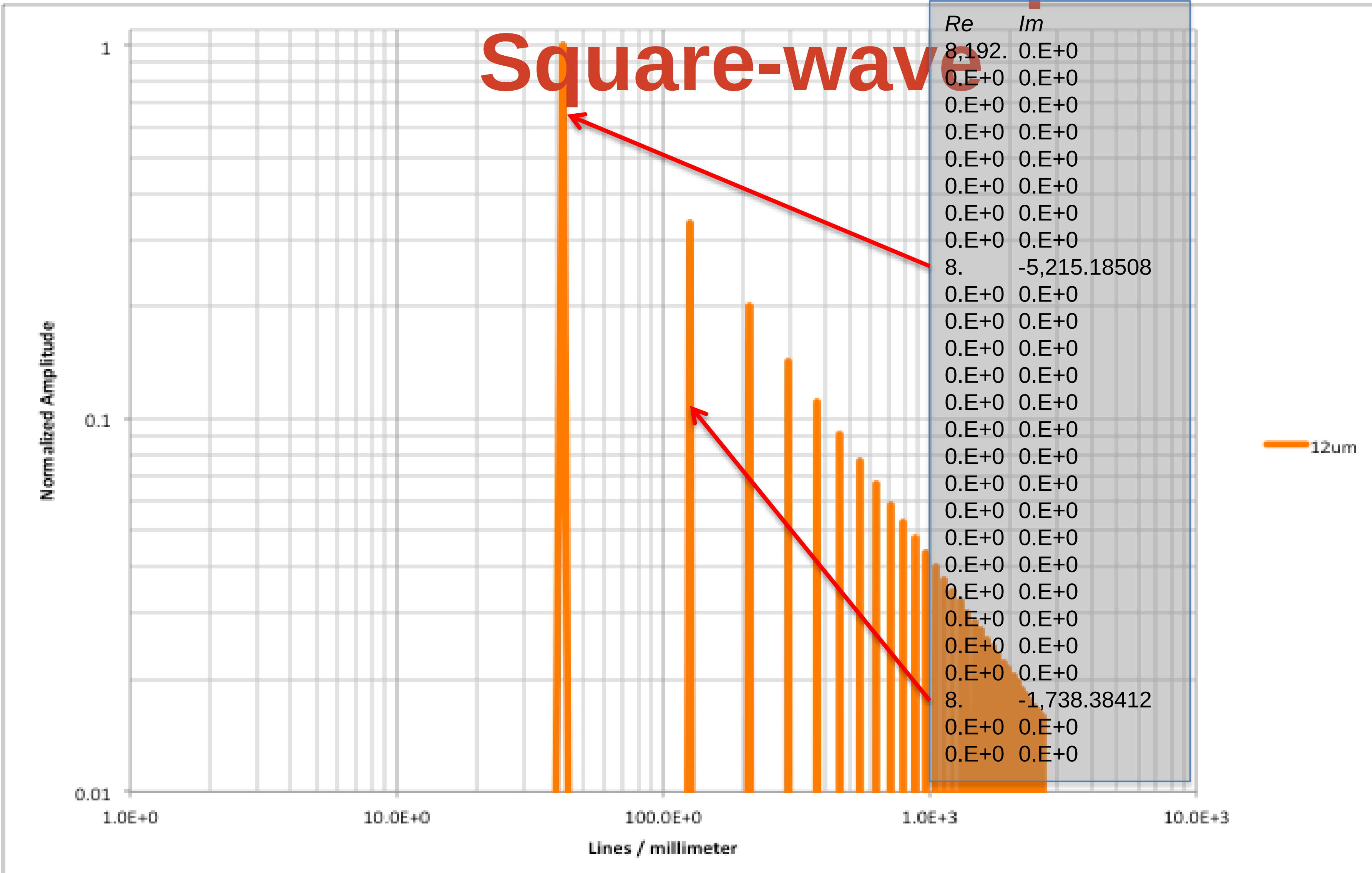
01111000011110000111100

01111111000000011111110

01111111111000000000011

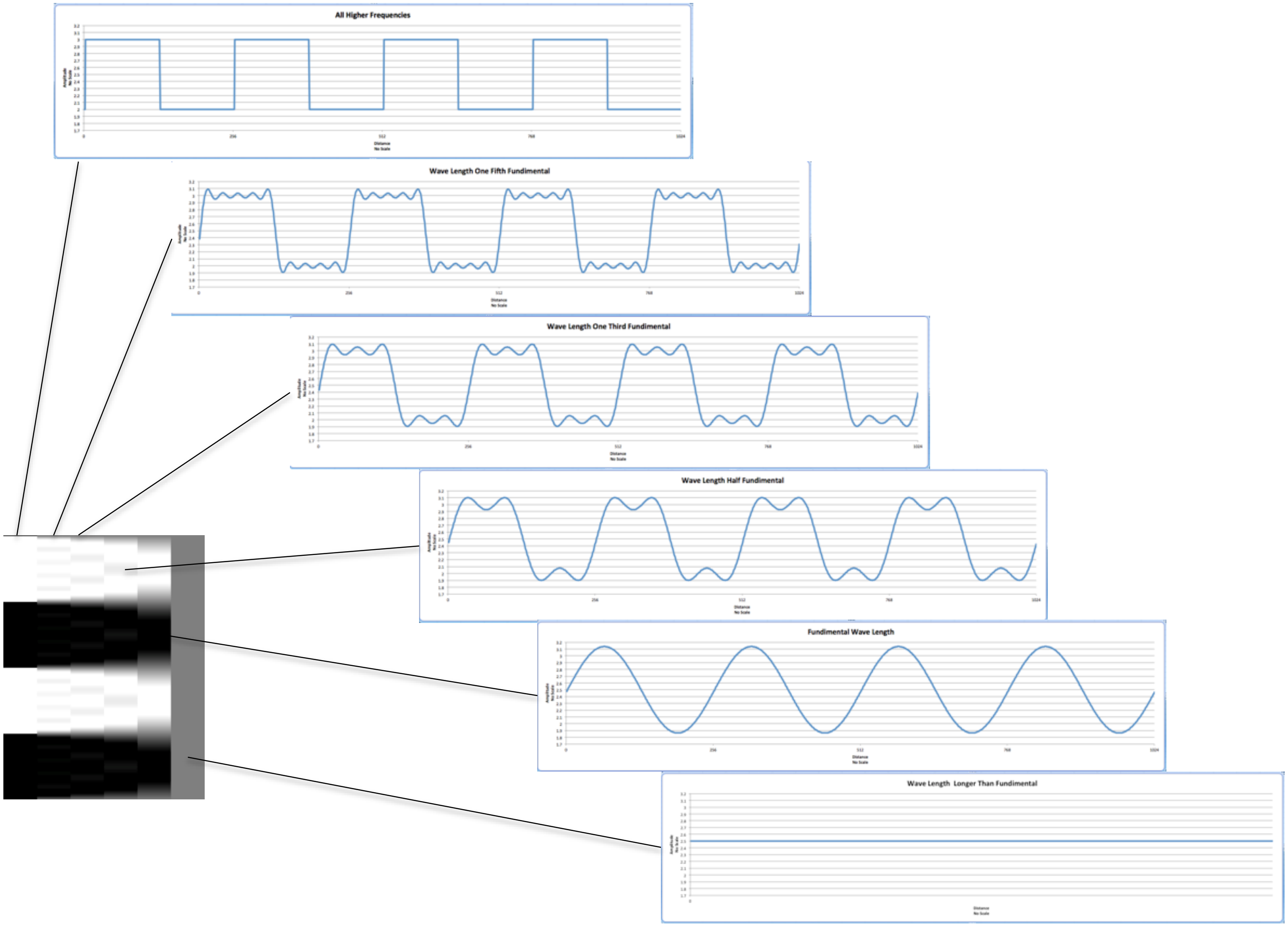
Not to scale

Fourier Transform of 12μm Square-wave

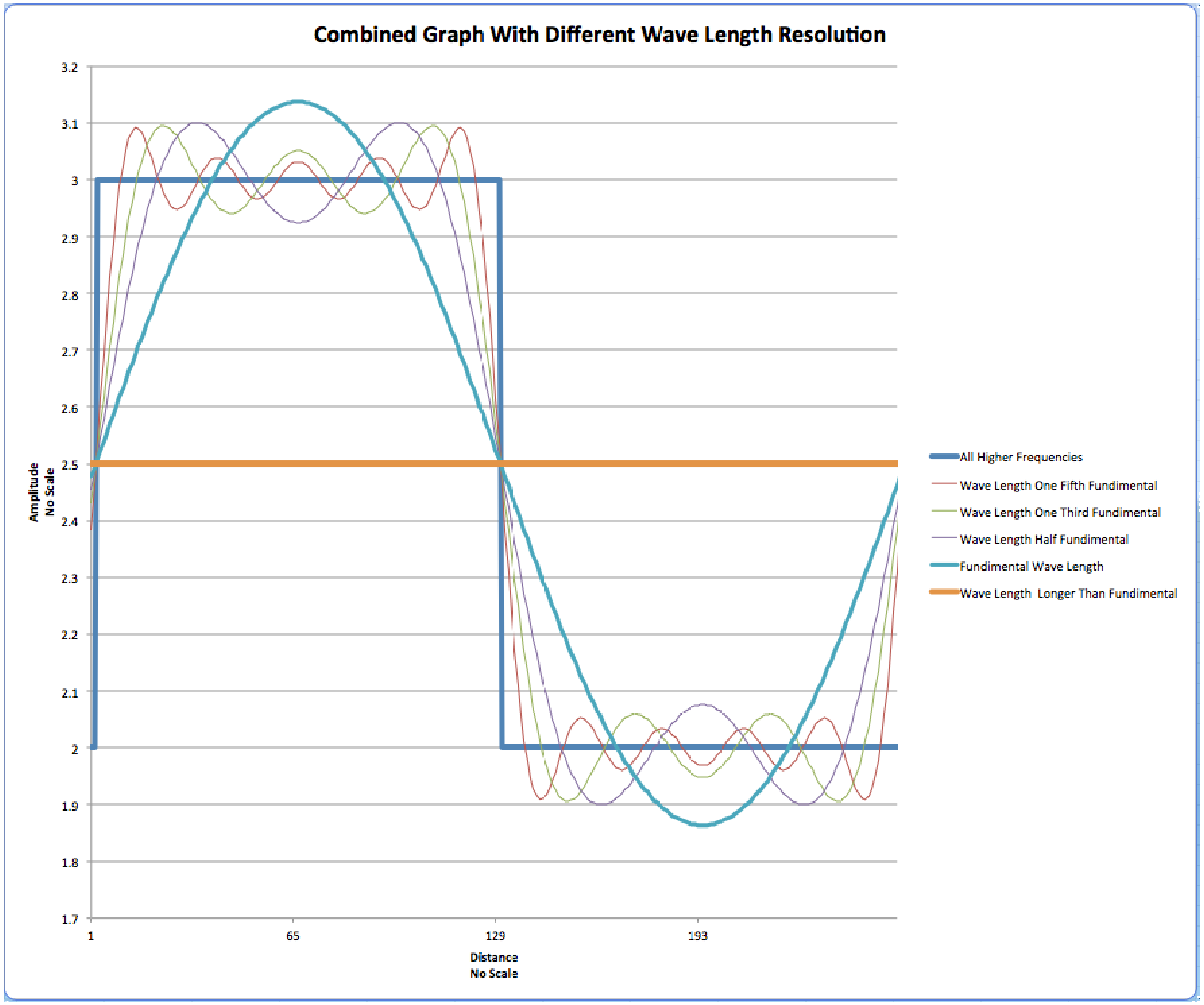


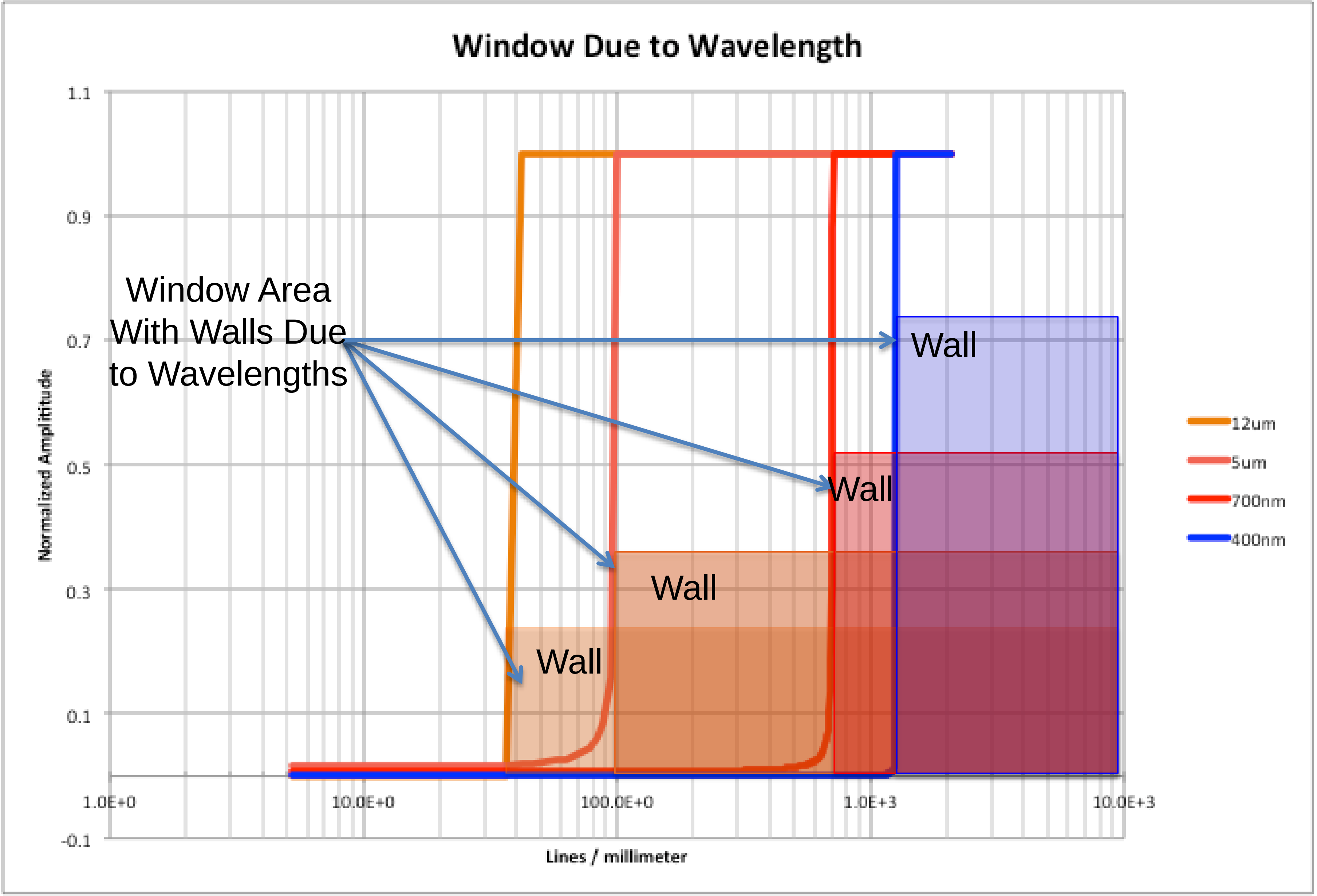
Re	*Im*
8,192.	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
8.	-5,215.18508
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
0.E+0	0.E+0
8.	-1,738.38412
0.E+0	0.E+0
0.E+0	0.E+0

Fourier Remove of Frequencies



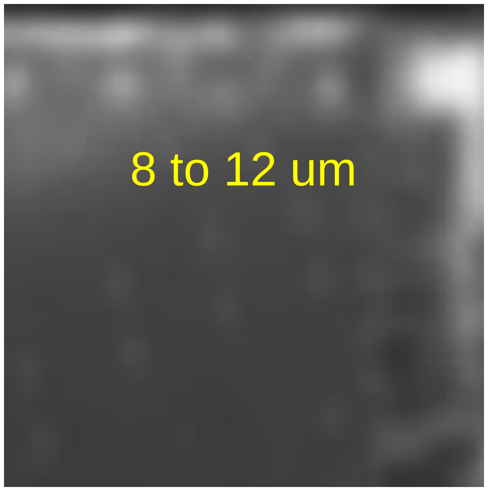
Fourier Remove of Frequencies

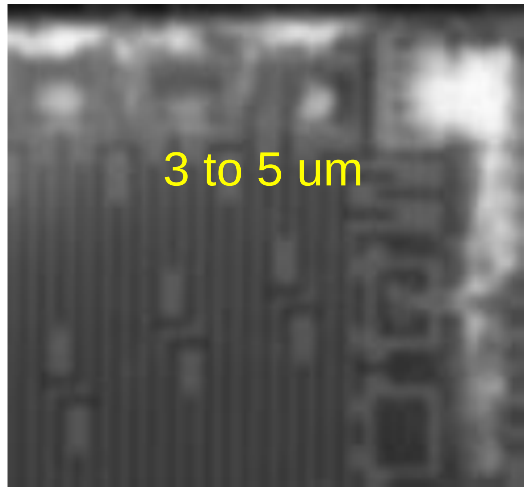


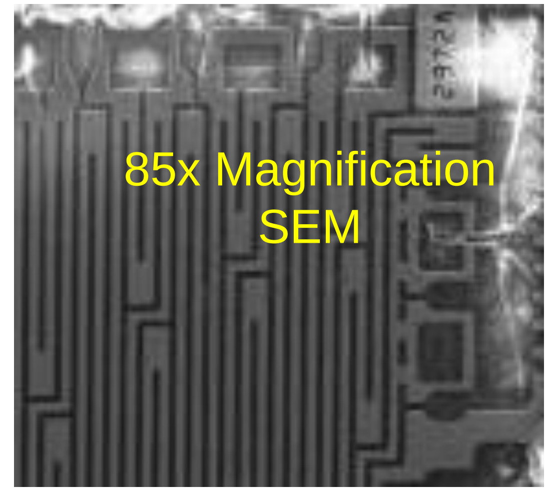


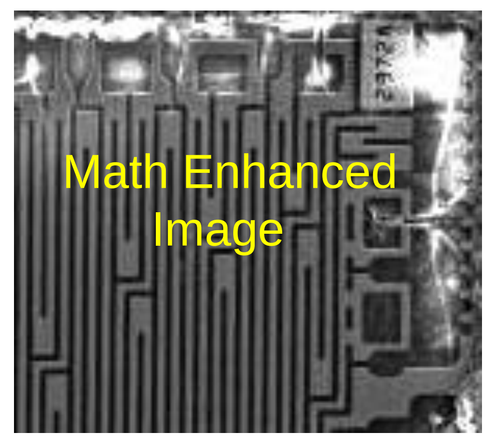
Window Due to Wavelength
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
Normalized Amplititude
Window Area
With Walls Due
to Wavelengths
Wall
Wall
Wall
Wall
1.0E+0
10.0E+0
100.0E+0
1.0E+3
10.0E+3
Lines / millimeter
12um
5um
700nm
400nm

Simulation of Resolution of different Wavelengths



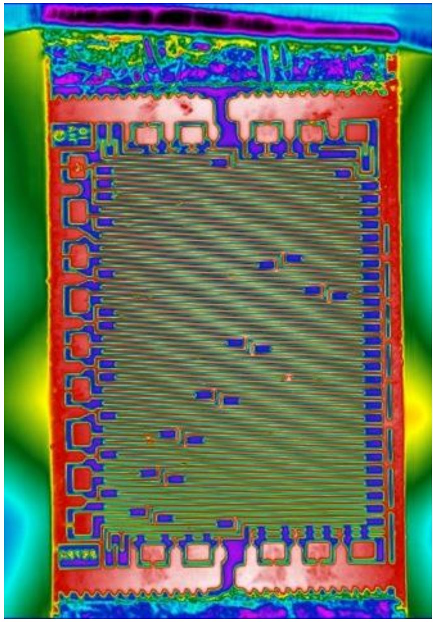






Conclusions

- Defects do cause hot spots
- There are test setup issues with using a Thermal Microscope.
  - Moiré Patterns



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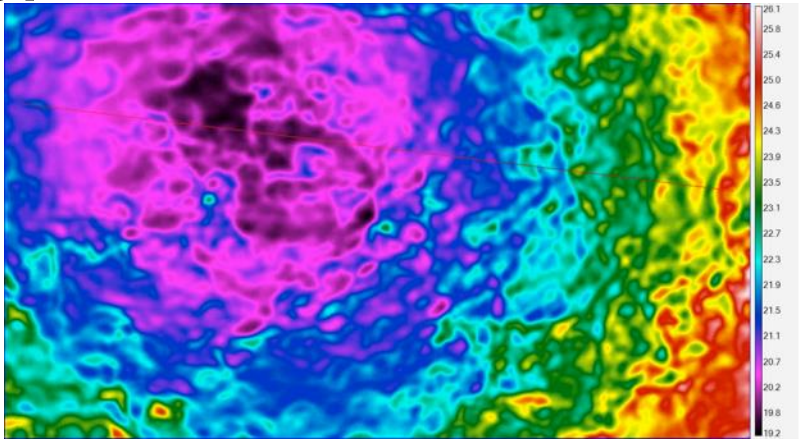

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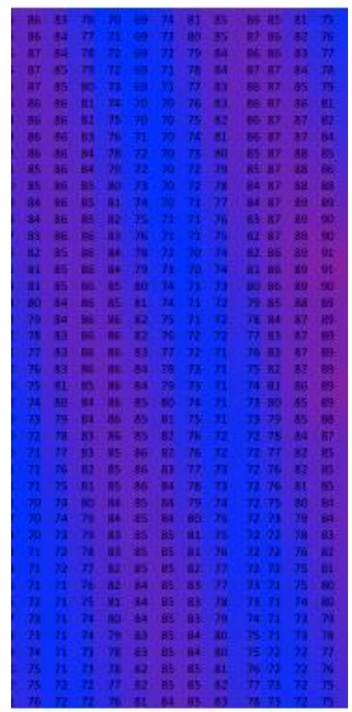
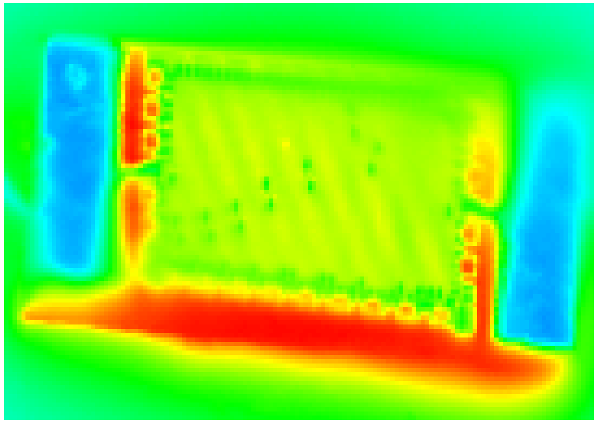


Conclusions

- Defects do cause hot spots
- There are test setup issues with using a Thermal Microscope.
  - Moiré Patterns
  - Narcissus effects
  - Emissivity
  - Limits on Resolution in the IR




Thank You